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THOR CERTIFICATION MANUAL

(Revision 2001.02)

TRAUMA ASSESSMENT DEVICE DEVELOPMENT PROGRAM

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THOR CERTIFICATION MANUAL

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THOR CERTIFICATION MANUAL

1. INTRODUCTION

This manual constitutes part of the final documentation for the NHTSA Advanced Frontal Dummy known as THOR (**T**est device for **H**uman **O**ccupant **R**estraints). It describes the certification procedures for qualifying the different components of the dummy. These are test procedures developed to verify the proper response characteristics of these components, normally under dynamic loading conditions. This manual can be used in conjunction with the document ***Biomechanical Response Requirements of the Thor NHTSA Advanced Frontal Dummy (Revision 2001.02)***. Several of the test procedures described in the latter document and used for evaluating the biofidelity of the Thor dummy are described in greater detail in this document.

In addition to the standard certification procedures, the present document also describes a number of additional test methods used for evaluating the characteristics of the deformable materials used within Thor. The responses of the materials under these procedures are meant to be used as design reference guides.

The document is arranged in two sections. In each section, the report is arranged according to the principal segments of the dummy. Section I contains the basic certification procedures for the dummy to ensure that the performance of the dummy is within the original design limits. Section II describes a set of test procedures which are used to check the properties of the materials used within the dummy and perform a preliminary check of selected components.

SECTION I. PRIMARY CERTIFICATION TESTS

2. HEAD CERTIFICATION

2.1 Head Impact

Summary

The standard test used for certifying the response of the Thor forehead is a frontal impact to the forehead by a rigid impactor [Melvin, 1985]. The result of this test should meet the specification stipulated here.

Reference

Melvin, J., Weber, K. 1985. *Task B Final Report.* UMTRI-85-3. University of Michigan Transportation Research Institute, Ann Arbor, MI.

Description

This dynamic test is performed to examine the force-time characteristic of the head in an impact with a rigid impactor of mass 23.4 kg. The impact velocity for this certification is 2.0 m/s.

Materials

The parts required for the head frontal impact test are:

1. Fully assembled dummy.
2. Linear impactor or impact pendulum with a mass of 23.4 kg. The impactor should be cylindrical with a circular face of diameter 152 mm. The impactor edge should have a radius of 12 mm.

Instrumentation

The instrumentation required for the test is:

1. Accelerometer or accelerometer / load cell for measuring the impact force.
2. Impact velocity measuring instrumentation.
3. Triaxial accelerometer mounted at the C.G. of the head

The polarity conventions and data acquisition system must conform to requirements of the 1996 revision of SAE Recommended Practice J211. Filter the pendulum accelerometer using filter class CFC 60, the load cell and accelerometer data channels using filter class CFC 1000.

Test Procedure

1. Inspect the head assembly for wear, tears, or other damage.
2. Soak dummy in a controlled environment at a temperature between 69° and 72°F for at least 4 hours prior to testing. The test environment should have the same temperature as the soak environment.
3. Seat the dummy on a seating surface with a back support and with the limbs extended horizontally forward (the shoulder and elbow joints can be tightened to the normal 1g level).
4. The impactor should be placed so that its axis is aimed at a point on the forehead on the midsagittal plane and 30 mm above the horizontal line marking the lowest limit of the forehead . The tilt of the dummy head/neck assembly should be adjusted so that the impact area is parallel to the face of the impactor.
5. The motion of the impactor should be constrained so that there is no significant lateral, vertical, or rotational movement.
6. Deliver the impactor at the speeds of 2.0 m/s. Note that at least 60 minutes should pass between two successive tests.

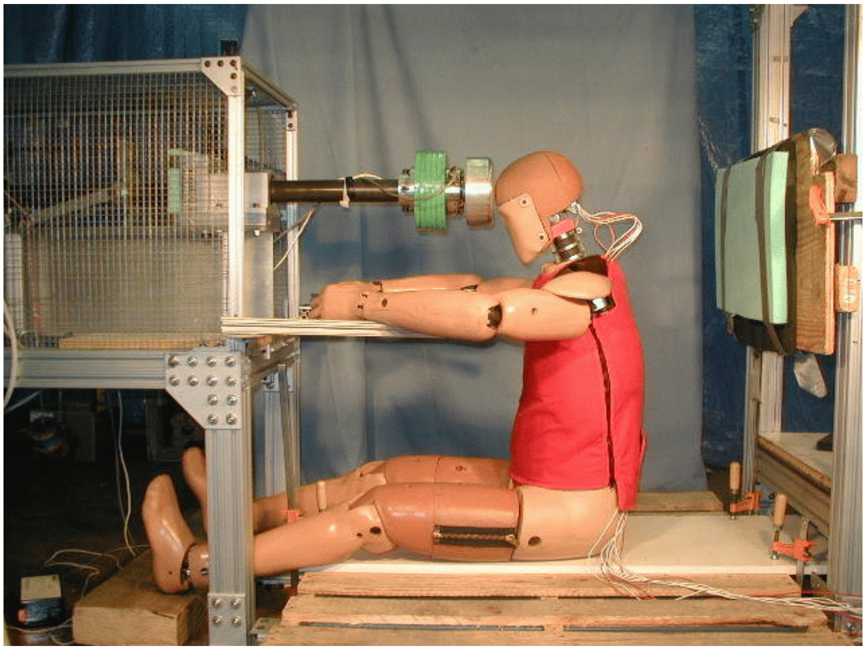


Figure 1. Setup for head impact test using linear impactor.

Performance Specification

The peak force and the time at which the peak force occurs are measured from the impact. These should be within the ranges provided in the table below.

Impact Speed (m/s)	Peak Force (N)	Time for Peak (msec)
2.0 m/s	5010 - 5830	2.0 - 3.0

The specification is shown graphically below. The original biomechanical response corridor is also shown.

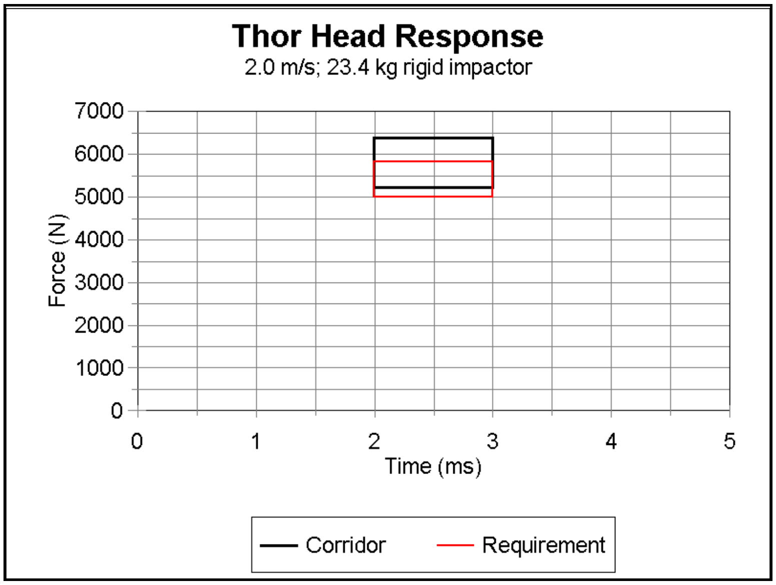


Figure 2. Force vs. time response for Thor head impact.

3. NECK CERTIFICATION

Summary

The standard test used for certifying the response of the Thor neck is with the neck and head assembly attached to the standard head-neck pendulum as defined in CFR Title 49, Part 572.

For design reference, a number of additional quasi-static tests are suggested. These are:
1. A quasi-static compression test on the rubber material of the neck used for evaluating the force-deflection characteristic of the neck material.
2. A series of quasi-static bending tests in frontal flexion, lateral flexion, and extension which evaluates the response of the total neck assembly in this configuration.

Reference

Code of Federal Regulations. 1998. *Title 49, Part 572, Subpart E.*

3.1 Neck Dynamic Response with Pendulum

Description

The test resembles the current test for the 50th percentile male head-neck assembly. The head/neck assembly is attached rigidly to the bottom of the head-neck pendulum. The pendulum test is used to define dynamic response in all three directions, namely: frontal, lateral, and extension.

Materials

The parts required for the head/neck pendulum test are:

1. Head and neck assembly, including all neck spring hardware
2. Head-neck pendulum (as defined in CFR Title 49, Part 572, Subpart E)
3. Foam padding used for decelerating the pendulum.

Instrumentation

The instrumentation required for the test is:

1. Upper neck 6-axis load cell.
2. Front and rear neck spring load cells.
3. Rotary potentiometer at the occipital condyle.
4. Pendulum accelerometer.

The polarity conventions and data acquisition system must conform to requirements of the 1996 revision of SAE Recommended Practice J211. Filter the pendulum accelerometer using filter class CFC 60, the load cell data channels using filter class CFC 600 and the rotary potentiometer using filter class CFC 180.

Test Procedure

1. Inspect the neck assembly for wear, tears, or other damage and for any debonding between the rubber pucks and metal plates. Inspect the front and rear springs (including the inserted rubber tubes) within the head assembly for any wear or other damage. Inspect the front and rear stops at the bottom of the head also for wear and damage.

2. Attach the neck assembly to the head and ensure that the O.C. potentiometer and housing are properly inserted.

3. Soak the head and neck assembly in a controlled environment at a temperature between 69° and 72°F for at least four hours prior to testing. The test environment should have the same temperature as the soak environment.

4. Mount the bottom of the neck assembly rigidly to the end plate of the head/neck pendulum. For the frontal flexion test, the neck is placed such that the mid-sagittal plane of the head is vertical and anterior-posterior direction of the assembly is pointing in the direction of travel of the pendulum. For the extension test, the direction is reversed. For the lateral flexion test, the base of the neck is rotated by 90° from the above.

5. Attach a rectangular section of Ensolite SCC High Performance foam to the impact area of the frame of the head-neck pendulum. The dimensions of the foam are:
   length = 136.5 mm; width = 101.6 mm; thickness = 76.2 mm.
   The foam can be attached by double-sided tape to the frame. It should be ensured that the contact area of the foam pad will completely cover the impactor plate on the pendulum upon impact.

   The response characteristics of the foam are determined from a quasi-static force-deflection test on a cubic specimen of dimensions of 50.8 mm x 50.8 mm x 50.8 mm. These are shown in the following table.

   Compression Characteristics of Ensolite SCC Foam

Deflection (mm)	Compression (%)	Force Range (N)
15	.30	240 - 270
25	.50	470 - 520

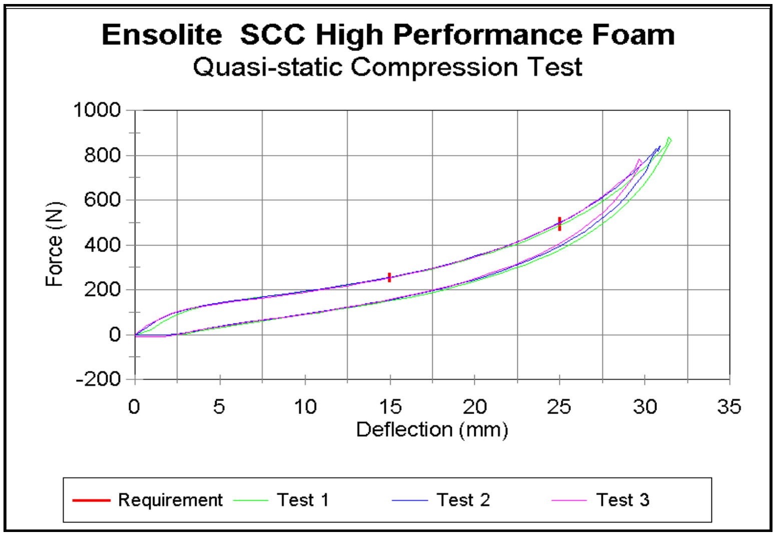


Figure 3. Force-deflection response of Ensolite SCC High Performance foam in quasi-static compression.

6. For the frontal flexion test, the pendulum should be released from a height to generate a 3.8 ± .1 m/s velocity at impact (equivalent to pendulum drop angle of 54.1°) . For the extension test, the pendulum should be released from a height to generate a 3.7 ± .1 m/s velocity at impact (equivalent to pendulum drop angle of 53.6°). For the lateral flexion test, the pendulum should be released from a height to generate a 2.9 ± .1 m/s velocity at impact (equivalent to pendulum drop angle of 40.3°).

7. Collect the time histories of the instrumentation channels above. The calculation procedure for the total moment at the O.C. is shown below and can also be determined using the accompanying THORTEST program. Using either method, compute the time history of the total neck moment (My) at the O.C.

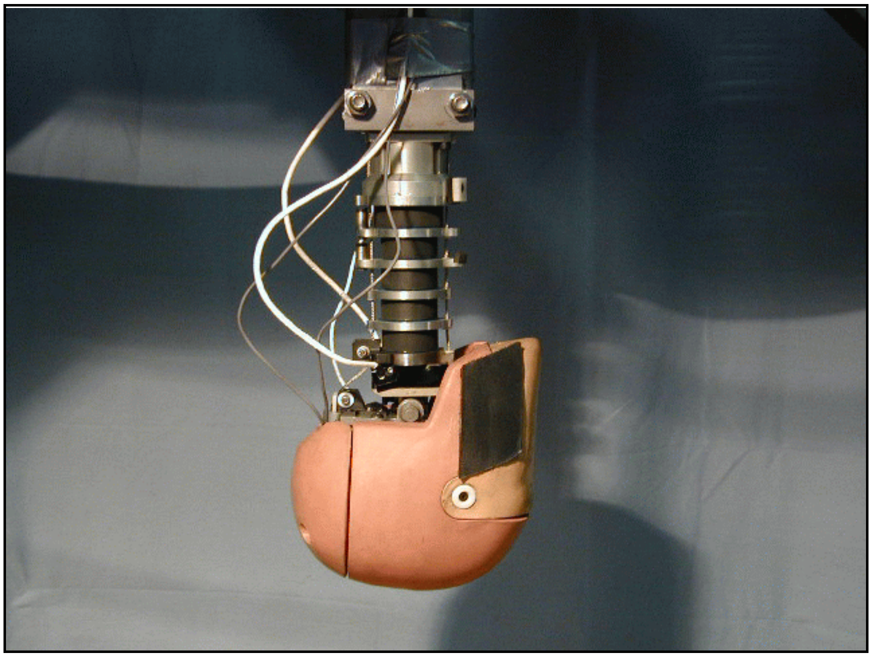


Figure 4. Setup for the neck pendulum test.

Data Processing

The moment at the O.C. is computed from the relation:

$$M_{OC} = M_y + a.F_x - r_f \times f_f + r_r \times f_r$$

where: F_x, M_y = shear X force and Y moment measured at load cell
a = offset of center of load cell from center of occipital condyle (O.C.) pin
r_f, r_r = vector location of front and rear neck spring cables relative to O.C. (from measurements on the head and neck)
f_f, f_r = vector forces along front and rear neck spring cables (from neck spring load cells)

Performance Specifications

<u>Frontal Flexion</u>

The response of the neck in frontal flexion is given by the following:

Pendulum Acceleration

Quantity	Units	Specification
Peak acceleration	g	24.0 - 28.0
Time for peak acceleration	msec	18.5 - 21.5
Duration	msec	35.1 - 40.8

Moment at O.C.

Quantity	Units	Specification
1st peak moment	Nm	52.2 - 63.8
Time for 1st peak moment	msec	67.5 - 82.5

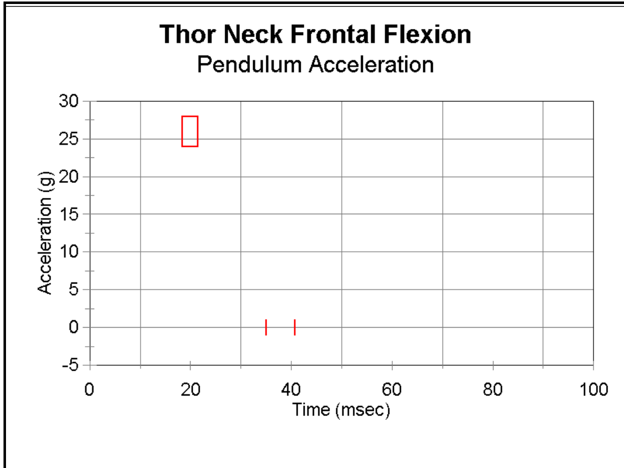


Figure 5. Pendulum acceleration response with head/neck pendulum in frontal flexion.

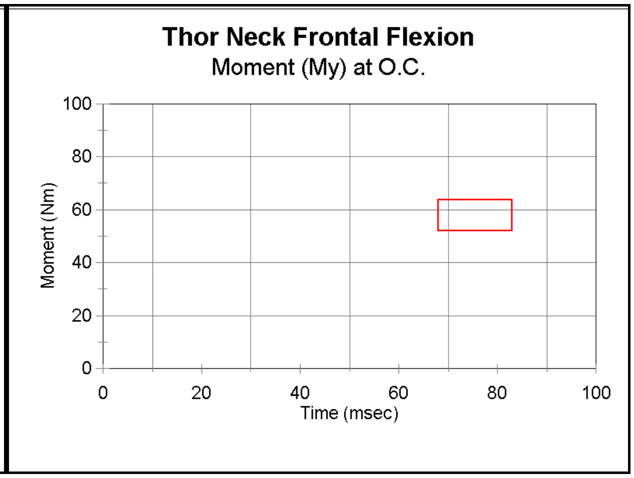


Figure 6. Neck My moment response at O.C. with head/neck pendulum in frontal flexion.

Extension

The response of the neck in extension is given by the following:

Pendulum Acceleration

Quantity	Units	Specification
Peak acceleration	g	23.1 - 26.9
Time for peak acceleration	msec	18.5 - 21.5
Duration	msec	36.1 - 41.9

Moment at O.C.

Quantity	Units	Specification
1st peak moment	Nm	-68.4 - -83.6
Time for 1st peak moment	msec	51.3 - 62.7

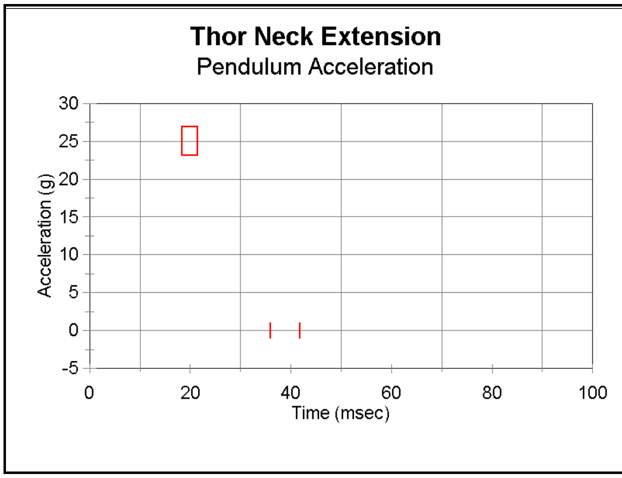


Figure 7. Pendulum acceleration response with head/neck pendulum in extension.

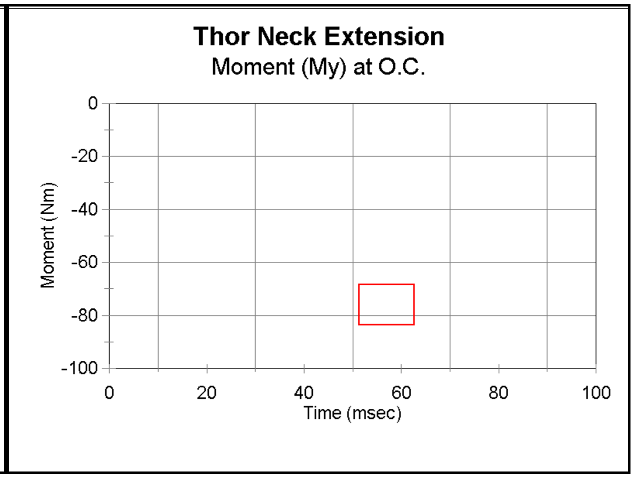


Figure 8. Neck My moment response at O.C. with head/neck pendulum in extension.

Lateral Flexion

The response of the neck in lateral flexion is given by the following:

Pendulum Acceleration

Quantity	Units	Specification
Peak acceleration	g	15.0 - 17.2
Time for peak acceleration	msec	20.2 - 23.4
Duration	msec	40.7 - 47.3

Moment at O.C.

Quantity	Units	Specification
1st peak moment	Nm	33.9 - 41.5
Time for 1st peak moment	msec	62.3 - 76.1

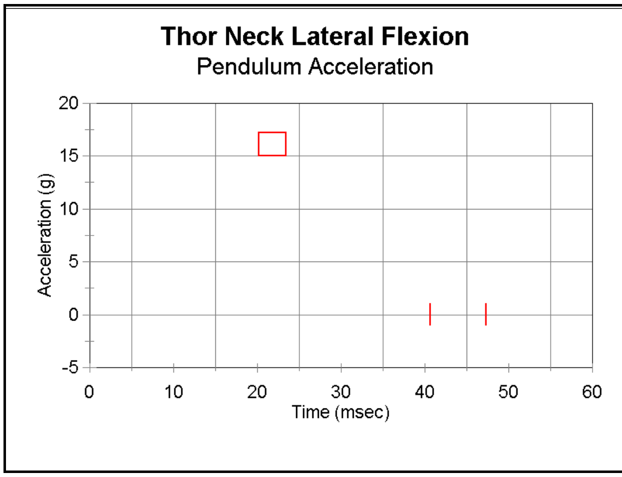


Figure 9. Pendulum acceleraton response for head/neck pendulum in lateral flexion.

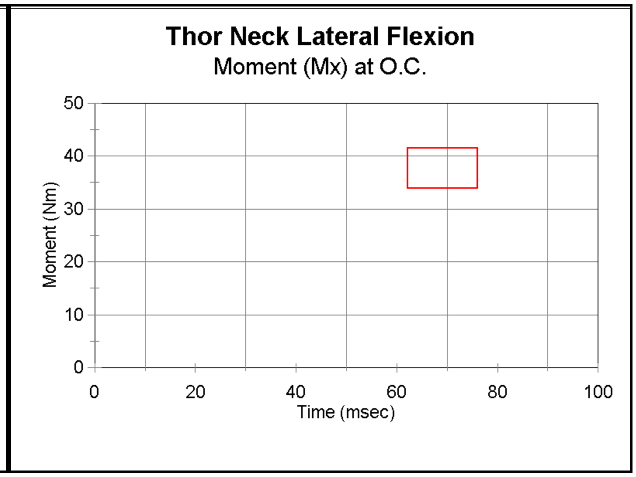


Figure 10. Neck Mx moment response at O.C. with head/neck pendulum in lateral flexion.

4. THORAX CERTIFICATION

Summary

The standard tests for certifying the response of the Thor thorax are the Kroell central impact tests to the sternum at 4.3 and 6.7 m/s [Neathery, 1974] and an oblique impact to the lower ribcage [Yoganandan, 1997]. In addition, the following tests have been defined to fully define the operation of the thorax. These tests may be used by the manufacturer to aid in the final thorax assembly.

1. Rib damping material quasi-static compression test
2. Bib material quasi-static tension test
3. Jacket material quasi-static tension test

References

Neathery, R. 1974. *Analysis of Chest Impact Response Data and Scaled Performance Recommendations.* Proceedings of the 18th Stapp Car Crash Conference.

Yoganandan, N., Pintar, F., Kumaresan, S., Haffner, M., Kuppa, S. 1997. *Impact biomechanics of the human thorax-abdomen complex*. International Journal of Crash, Vol 2, No. 2, pp 219-228

4.1 Upper Ribcage Central Impact Test

Description

The principal response corridors required to be met by THOR for thoracic impact are the traditional Kroell corridors for rigid disk impacts to the mid-sternum at 6.7 m/s and 4.3 m/s. The normalized curves, showing the impact force vs. chest deflection define the appropriate response requirements for these types of impacts for a 50th percentile U.S. male.

Materials

The parts required for performing the Kroell test are:

1. Fully assembled Thor dummy with internal Crux units
2. Impact fixture: either impact pendulum or linear impactor with appropriate mass and velocity

Instrumentation

The required instrumentation for this test is:

1. Instrumentation to measure impact force (impact accelerometer on impactor or load cell / accelerometer combination)
2. Four Crux units attached to the standard upper and lower thorax locations.

The polarity conventions and data acquisition system must conform to requirements of the 1996 revision of SAE Recommended Practice J211. The impactor load cell and accelerometer should be filtered with CFC 600. The rotary potentiometers on the Crux should be filtered with CFC 180. Suggested sampling rates for the A/D conversion is 10 ksamples/sec

Test Procedure

The test configuration for performing the Kroell tests using the 50th percentile male THOR ATD consists of:

1. Inspect the ribcage, bibs, and jacket for wear, tears, or other damage. Prior to assembly the profiles of the ribs should be examined to determine if they have been permanently deformed.

2. Soak the dummy in a controlled environment at a temperature between 69° and 72°F overnight prior to testing. The test environment should have the same temperature as the soak environment.
   NOTE: Care should be taken to ensure the ambient temperature is well controlled within the above limits since the rib material is very temperature sensitive.
3. The impactor should be rigid and flat with a 152 mm diameter and mass of 23.4 kg. The edge of the impactor face should have a radius of 12.5 mm.
4. The dummy is set up in a sitting position, with no back support and its legs horizontal and the arms raised (may be taped lightly to a support bar).
5. Dummy is positioned in front of impactor such that the center line of the impactor is at the vertical level of the middle of dummy rib #3, and positioned over the mid-line of the sternum. This position would be at the middle of the line connecting the attachment nuts of the two upper chest deflection measurement systems (Crux). The impactor face should be approximately parallel to the chest at this location. This requires the lower thoracic spine to be 0° - 4° bent forward relative to vertical.
6. Two impact speeds are tested: one at 6.7 m/s and one at 4.3 m/s.
7. The measurements include the impact force measured at the impactor and deflections measured by the two upper Crux systems. The average of the right and left X deflections should be used as the measure for chest skeletal deflection.

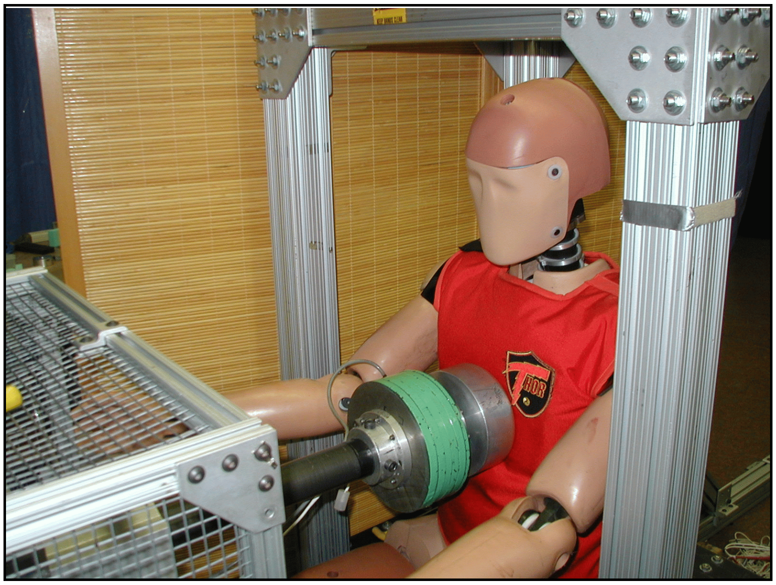


Figure 11. Setup of sternal impact test for measuring upper ribcage response.

Data Processing

The impactor can either be a pendulum or a linear impactor with the desired mass and geometry.

The measurements include:

1. Impact force at the contact face: This can be measured in either of two ways:
    1. With a single linear accelerometer along the line of impact
    2. With an in-line load cell measuring axial force and a linear accelerometer along the line of impact. In this case, the mass in front of the load cell, including half the load cell mass should be recorded to determine the inertial correction to the load cell reading. The impact force is given by:

       $$F_i = -F_{LC} + m_f a$$

       where: F_{LC} = load cell measurement
       m_f = mass in front of load cell
       a = impactor acceleration

2. Upper left and right Crux measurements: These comprise the potentiometer data from each of the Crux units. Process the Crux potentiometer data using the supplied THORTEST program to determine the X, Y, and Z deflections.

Performance Specifications

The specifications for the Kroell impact are:

Table 1.   4.3 m/s Sternal Impact

Parameter	**Value**
Initial Peak	Force (N): 1750 - 2750 Defl (mm): 2.0 - 10.0
Max. Force	Force (N): 2610 - 3190 Defl (mm): 42.3 - 51.7
Max. X Deflection	Force (N): 2295 - 2805 Defl (mm): 45.0 - 55.0
Hysteresis	70% - 88%

Table 2. 4.3 m/s Sternal Impact Response Corridor

	X Deflection (mm)	Force (N)
Upper limit	6.35	3293
	25.4	3115
	38.1	3115
	53.34	3560
	63.5	2670
	58.42	890
Lower limit	6.35	2492
	25.4	2314
	38.1	2314
	46.99	2581
	43.18	890

Table 3. 6.7 m/s Sternal Impact

Parameter	Value
Initial Peak	Force (N): 2800 - 4200 Defl (mm): 3.0 - 10.0
Max. Force	Force (N): 4900 - 6000 Defl (mm): 59.4 - 72.6
Max. X Deflection	Force (N): 4680 - 5720 Defl (mm): 63.0 - 77.0
Hysteresis	70% - 88%

Table 4. 6.7 m/s Sternal Impact Response Corridor

<table>
<tr><th></th><th>X Deflection (mm)</th><th>Force (N)</th></tr>
<tr><td rowspan="7">Upper limit</td><td>6.35</td><td>4361</td></tr>
<tr><td>25.4</td><td>4539</td></tr>
<tr><td>38.1</td><td>4806</td></tr>
<tr><td>62.23</td><td>5429</td></tr>
<tr><td>77.47</td><td>4450</td></tr>
<tr><td>82.55</td><td>3115</td></tr>
<tr><td>73.66</td><td>890</td></tr>
<tr><td rowspan="6">Lower limit</td><td>6.35</td><td>3293</td></tr>
<tr><td>25.4</td><td>3382</td></tr>
<tr><td>38.1</td><td>3560</td></tr>
<tr><td>58.42</td><td>4005</td></tr>
<tr><td>60.96</td><td>3115</td></tr>
<tr><td>52.07</td><td>890</td></tr>
</table>

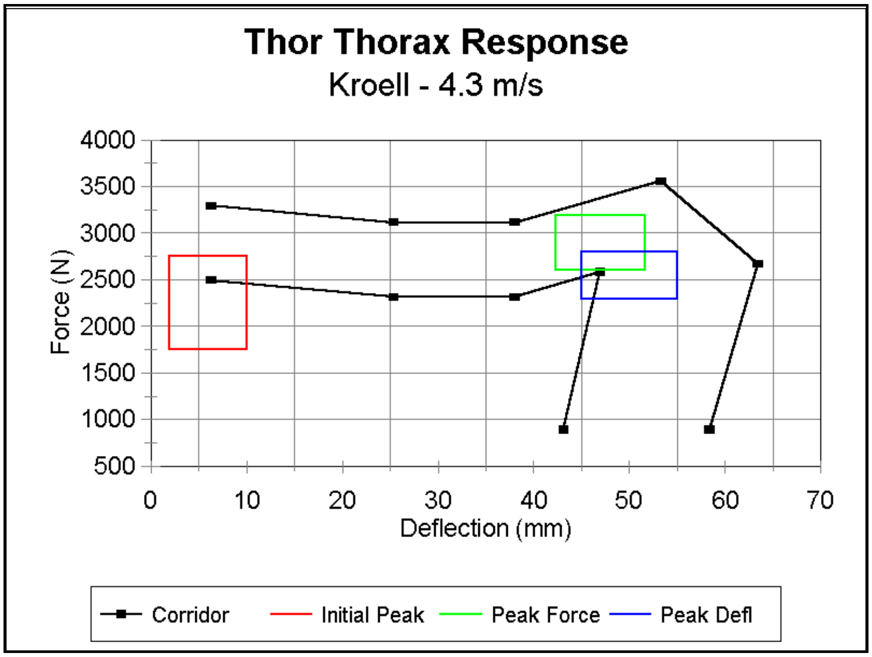


Figure 12. Force-deflection corridor for 4.3 m/s sternal impact (from Neathery).

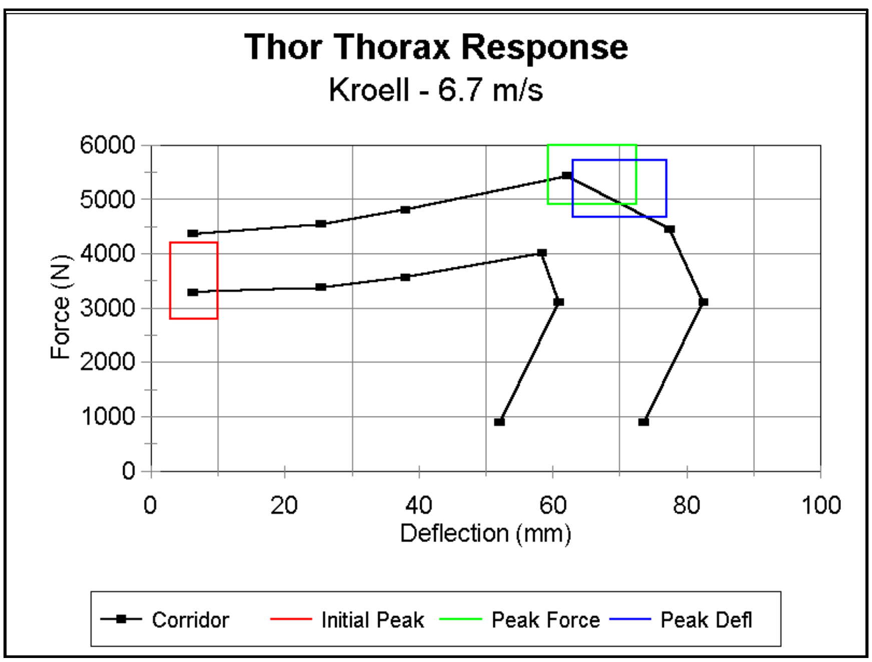


Figure 13. Force-deflection corridor for 6.7 m/s sternal impact (from Neathery).

4.2 Lower Ribcage Oblique Impact Test

Description

This test is based on oblique impacts at the lower ribcage performed by Medical College of Wisconsin (MCW) [Yoganandan, 1997]. In these tests, the torso was initially rotated from right to left by 15°, such that the impact occurred on the right antero-lateral thorax. The instrumentation in the MCW tests consisted of a load cell and uniaxial accelerometer attached to the pendulum to measure the impact forces. The chest deflection was measured with a chest band which measures the external deformation of the thorax. The response characteristics of the lower ribcage are shown as a force-time corridor, a deflection-time corridor and a combined force-deflection corridor.

Materials

The parts required for performing the lower ribcage oblique impact test are:

1. Fully assembled Thor dummy with internal Crux units
2. Impact fixture: either impact pendulum or linear impactor with appropriate mass and velocity

Instrumentation

The required instrumentation for this test is:

1. Instrumentation to measure impact force (impact accelerometer on impactor or load cell / accelerometer combination)
2. Four Crux units attached to the standard upper and lower thorax locations.

The polarity conventions and data acquisition system must conform to requirements of the 1996 revision of SAE Recommended Practice J211. The impactor load cell and accelerometer should be filtered with CFC 600. The rotary potentiometers on the Crux should be filtered with CFC 180. Suggested sampling rates for the A/D conversion is 10ksamples/sec

Test Procedure

1. Inspect the ribcage, bibs, and jacket for wear, tears, or other damage. Prior to assembly the profiles of the ribs should be examined to determine if they have been permanently deformed.

2. Soak the dummy in a controlled environment at a temperature between 69° and 72°F overnight prior to testing. The test environment should have the same temperature as the soak environment.
   NOTE: Care should be taken to ensure the ambient temperature is well controlled within the above limits since the rib material is very temperature sensitive.

3. The lower extremities are stretched horizontally and the upper extremities are extended forward to allow positioning of the torso. The back of the torso was unsupported.
4. Impact loading is applied at the level of the sixth rib in the anterior region on the right side.
5. The moving impactor mass is approximately 23.5 kg. and the impacting surface is a rigid (aluminum) disk of 150 mm. The impact surface is covered with 2 pieces of 9.5 mm thick and 150 mm diameter Rubatex foam ® 451N). The force-deflection characteristics of the padding, in quasi-static compression, are shown in the graph below.

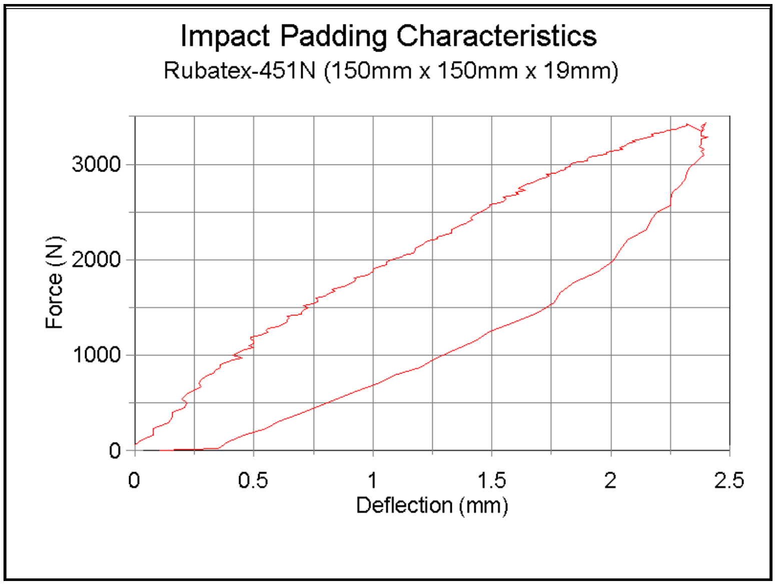


Figure 14. Quasi-static force-deflections characteristics of padding used in oblique impacts of lower ribcage.

6. The impact velocity is approximately 4.3 m/s.
7. The spinal posture is adjusted to the slouch position to keep the setting consistent with Kroell test setup.
8. Long underwear is placed on the dummy to provide realistic seat interaction.
9. The dummy is seated facing the impactor on a thin Teflon sheet. The teflon sheet is free to move relative to the wooden board attached to the test bed.
10. A clear acrylic plate with markings for every 15 degrees of rotation is attached to the top of the test bed. The center of the plate or 0 degree mark is oriented that when viewed from above (through the acrylic), it is in line with the posterior most point on the base aluminum neck plate. This point is selected to allow rotation of the dummy about its spine. The dummy is rotated 15 degrees from left to right about the spine.

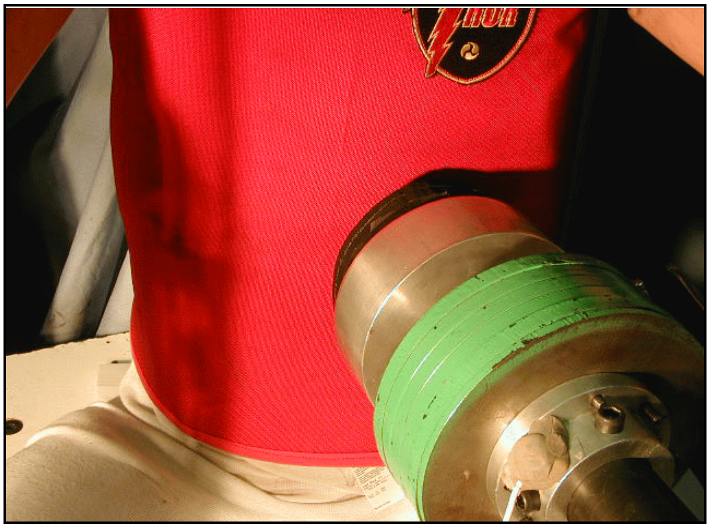


Figure 15. Setup of lower ribcage oblique impact

Data Processing

The impactor can either be a pendulum or a linear impactor with the desired mass and geometry. The measurements include:

1. Impact force at the contact face: This can be measured in either of two ways:
    1. With a single linear accelerometer along the line of impact
    2. With an in-line load cell measuring axial force and a linear accelerometer along the line of impact. In this case, the mass in front of the load cell, including half the load cell mass should be recorded to determine the inertial correction to the load cell reading. The impact force is given by:

    $$F_i = -F_{LC} + m_f a$$

    where: F_{LC} = load cell measurement
    m_f = mass in front of load cell
    a = impactor acceleration

2. Both lower Crux units are installed. Process the Crux potentiometer data using the supplied THORTEST program to determine the X, Y, and Z deflections. Calculate the effective deflection of the ribcage by combining the X and Y deflections from the Crux on the impacted side by the formula:

    $$d = X\cos\theta + Y\sin\theta$$

    Find the maximum value of d and the maximum value for F_i

Performance Specifications

The specifications for the lower ribcage oblique impact are given by the peak force and peak internal deflection as computed above.

Table 5. MCW Lower ribcage response requirement

Quantity	Units	Specification
Peak Force	N	3150 - 3850
Peak Displacement	mm	40 - 50

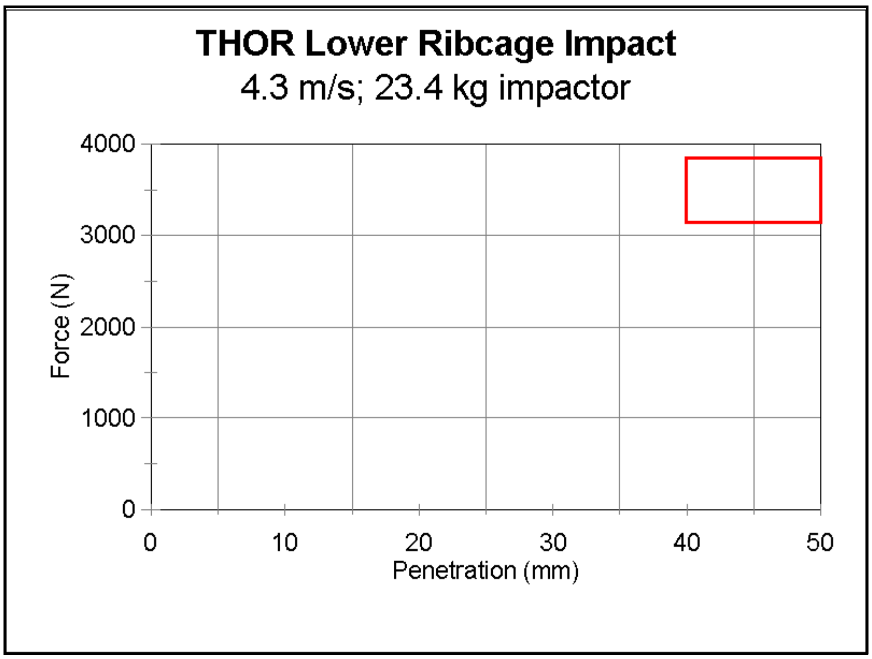


Figure 16. Force-deflection specification for oblique impact to lower ribcage at 4.3 m/s.

5. ABDOMEN CERTIFICATION

Summary

The standard tests used for certifying the response of the abdomen consist of an impact test with a cylindrical rod against the lower abdomen [Cavanaugh, 1986] and a steering wheel shaped impactor against the upper abdomen [Nusholtz, 1992].

For design reference additional quasi-static tests are suggested. These are the quasi-static compression tests on the two foam materials of the abdomen to evaluate the force-deflection characteristics of the materials.

References

Cavanaugh, J., Nyquist, G., Goldberg, S., and King, A. 1986. *Lower Abdominal Tolerance and Response.* Proceedings of the 30th Stapp Car Crash Conference.

Nusholtz, G., and Kaiker, P. 1994. *Abdominal Response to Steering Wheel Loading.* Proceedings of the 14th International Conference on Experimental Safety Vehicles.

5.1 Upper Abdomen Dynamic Impact Test

Description

The response requirement for upper abdomen impact has been derived from data developed by Nusholtz [1994] based on steering wheel impacts with engagement at region L2. The requirement is in the form of a force vs penetration corridor. Six tests were performed with impact speeds of 3.9 m/s to 10.8 m/s with an average speed of 8.0 m/s.

Materials

The parts required for performing the upper abdomen impact test are:

1. Fully assembled Thor dummy with left and right internal DGSP units in the abdomen.
2. Impact fixture: either impact pendulum or linear impactor with rigid, steering wheel shaped impact face. A sketch of the steering wheel geometry is shown in the following figure.

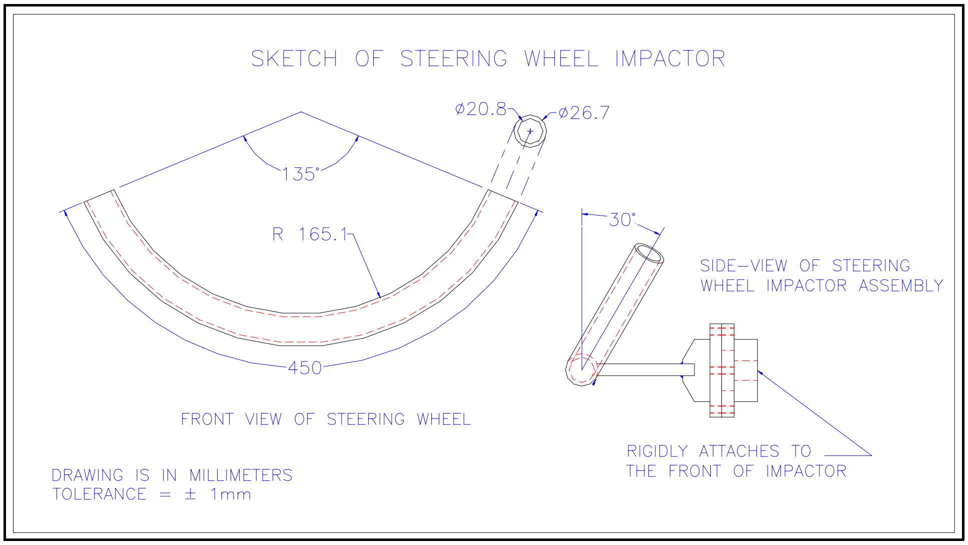


Figure 17. Dimensions and geometry of steering wheel impactor.

Instrumentation

The required instrumentation for this test is:

1. Instrumentation to measure impact force (impact accelerometer on impactor or load cell / accelerometer combination).
2. Upper abdomen string potentiometer.

The polarity conventions and data acquisition system must conform to requirements of the 1996 revision of SAE Recommended Practice J211. The impactor load cell and accelerometer should be filtered with CFC 600. The string potentiometer should be filtered with CFC 180. Suggested sampling rates for the A/D conversion is 10k samples/sec

Test Procedure

1. Inspect the abdomen foam and the outer Cordura covering for wear, tears, or other damage. Prior to assembly the abdomen should also be inspected for any permanent set.
2. Soak the dummy in a controlled environment at a temperature between 69° and 72°F overnight prior to testing. The test environment should have the same temperature as the soak environment.
3. The dummy is dressed in long thermal type pants. The dummy is seated on a thin plastic sheet. The lower extremities are stretched horizontally and the upper extremities are extended forward to allow positioning of the torso. The back of the torso was unsupported.
4. The spine pitch change is adjusted to the slouch position. The lower thoracic spine is maintained in a vertical position.

5. Impactor is in the shape of a steering wheel, mounted at an angle of 45° to the horizontal axis with a mass of 18 kg.
6. The leading edge of the steering wheel is set at the vertical level of the lower edge of the upper abdomen bag.
7. The impact velocity is 8.0 m/s.
8. The normal certification procedure will be to determine the penetration directly from the maximum displacement measured by the upper abdomen string potentiometer, and the maximum force measured from the impactor.

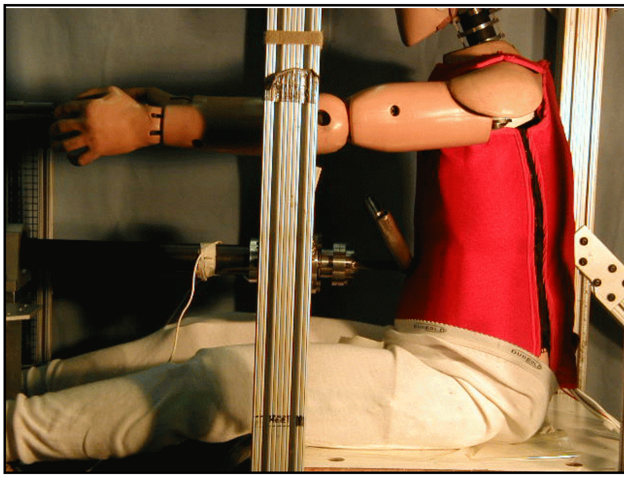


Figure 18. Setup of upper abdomen test (side view)

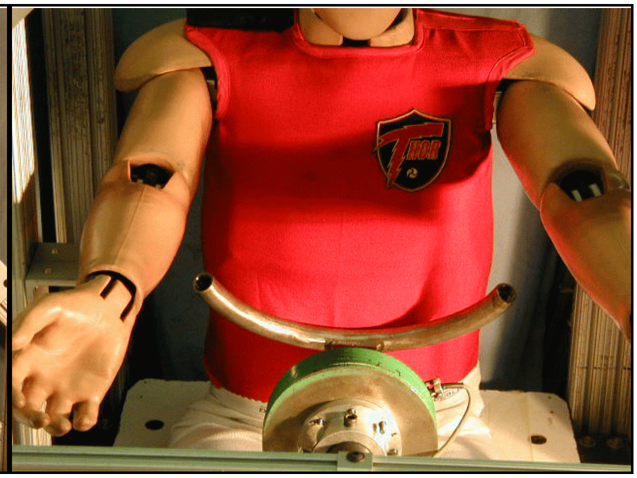


Figure 19. Setup of upper abdomen test (front view)

Data Processing

The impactor can either be a pendulum or a linear impactor with the desired mass and geometry. The measurements include:

1. Impact force at the contact face: This can be measured in either of two ways:
    1. With a single linear accelerometer along the line of impact
    2. With an in-line load cell measuring axial force and a linear accelerometer along the line of impact. In this case, the mass in front of the load cell, including half the load cell mass should be recorded to determine the inertial correction to the load cell reading. The impact force is given by:

$$F_i = -F_{LC} + m_f a$$

where: F_{LC} = load cell measurement
m_f = mass in front of load cell
a = impactor acceleration

2. Upper abdomen string potentiometer measurement: (CFC: 180)

Performance Specifications

The specifications for the upper abdomen impact are given by:

Table 6. Upper abdomen response requirement (8.0 m/s)

Quantity	Units	Specification
Peak Force	N	5625 - 6875
Peak Displacement	mm	37 - 45

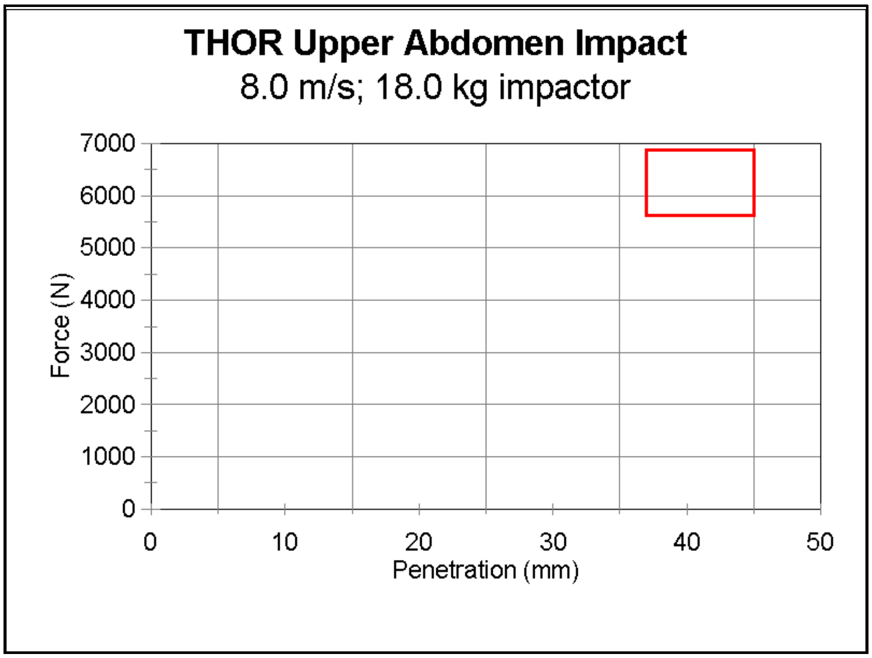


Figure 20. Force-penetration corridor for upper abdomen impact at 8.0 m/s.

5.2 Lower Abdomen Dynamic Impact Test

Description

The response requirement for lower abdomen impact has been derived from the low severity tests performed by Cavanaugh [1986]. The requirement is in the form of a force vs penetration corridor. The tests were conducted using a 25 mm diameter rigid bar of length 30 cm and mass 32 kg, impacting perpendicularly the abdomen of cadavers at vertical location of approximately L3. Five tests were performed in the speed range of 4.9 to 7.2 m/s with an average impact speed of 6.1 m/s.

Materials

The parts required for performing the lower abdomen impact test are:

1. Fully assembled Thor dummy with left and right internal DGSP units in the abdomen.
2. Impact fixture: either impact pendulum or linear impactor with appropriate mass and velocity

Instrumentation

The required instrumentation for this test is:

1. Instrumentation to measure impact force (impact accelerometer on impactor or load cell / accelerometer combination)
2. The two DGSP units attached to the lower abdomen.

The polarity conventions and data acquisition system must conform to requirements of the 1996 revision of SAE Recommended Practice J211. The impactor load cell and accelerometer should be filtered with CFC 600. The string and rotary potentiometers in the DGSP should be filtered with CFC 180. Suggested sampling rates for the A/D conversion is 10 ksamples/sec

Test Procedure

1. Inspect the abdomen foam and the outer Cordura covering for wear, tears, or other damage. Prior to assembly the abdomen should also be inspected for any permanent set.
2. Soak the dummy in a controlled environment at a temperature between 69° and 72°F overnight prior to testing. The test environment should have the same temperature as the soak environment.
3. The lower extremities are stretched horizontally and the upper extremities are extended forward to allow positioning of the torso. The back of the torso was unsupported.
4. The lower thoracic spine is maintained in a vertical position and the center line of the impactor should be at the vertical level of the line joining the centers of the attachment nuts of the right and left DGSPs and aimed at the mid-point of this line.
5. Impactor is a 25 mm diameter, 30 cm long rigid cylindrical rod with mass of 32 kg
6. The impact velocity is approximately 6.1 m/s.
7. The normal certification procedure will be to determine the penetration directly from average of the X component of the deflection measured by the two DGSPs within the abdomen and the external impactor force. A corresponding external measurement may be obtained using a linear displacement transducer.

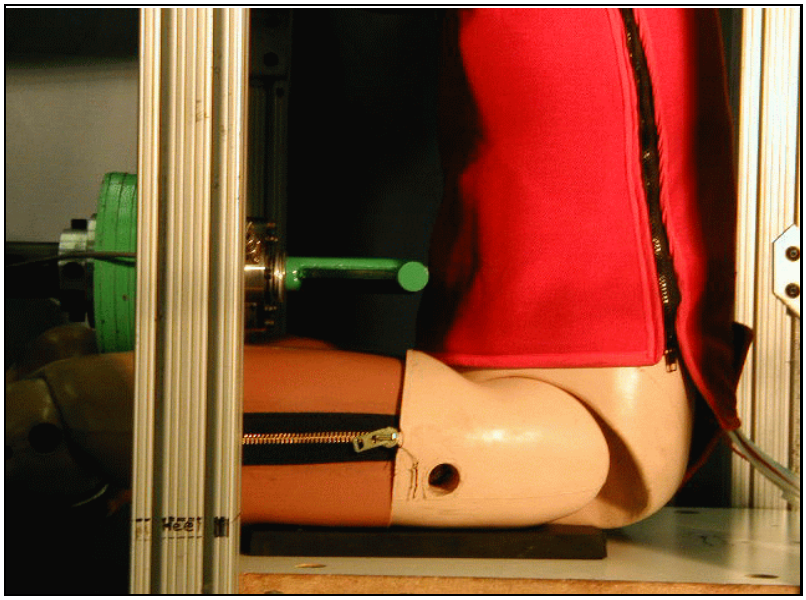


Figure 21. Setup of lower abdomen rod impact test

Data Processing

The impactor can either be a pendulum or a linear impactor with the desired mass and geometry. The measurements include:

1. Impact force at the contact face: This can be measured in either of two ways:
    1. With a single linear accelerometer along the line of impact
    2. With an in-line load cell measuring axial force and a linear accelerometer along the line of impact. In this case, the mass in front of the load cell, including half the load cell mass should be recorded to determine the inertial correction to the load cell reading. The impact force is given by:

       $$F_i = -F_{LC} + m_f a$$

       where: F_{LC} = load cell measurement
       m_f = mass in front of load cell
       a = impactor acceleration

2. Left and right DGSP measurements: These comprise the potentiometer data from each of the DGSP units. (CFC: 180)

Performance Specifications

The specification for the lower abdomen impact at 6.1 m/s is given by the impact force corridor for an internal deflection of 50 mm (as computed from the average of the X displacements measured by the left and right DGSPs).

Table 7. Lower abdomen response requirement (6.1 m/s)

Deflection (mm)	Force (N)
50	2200 - 2700

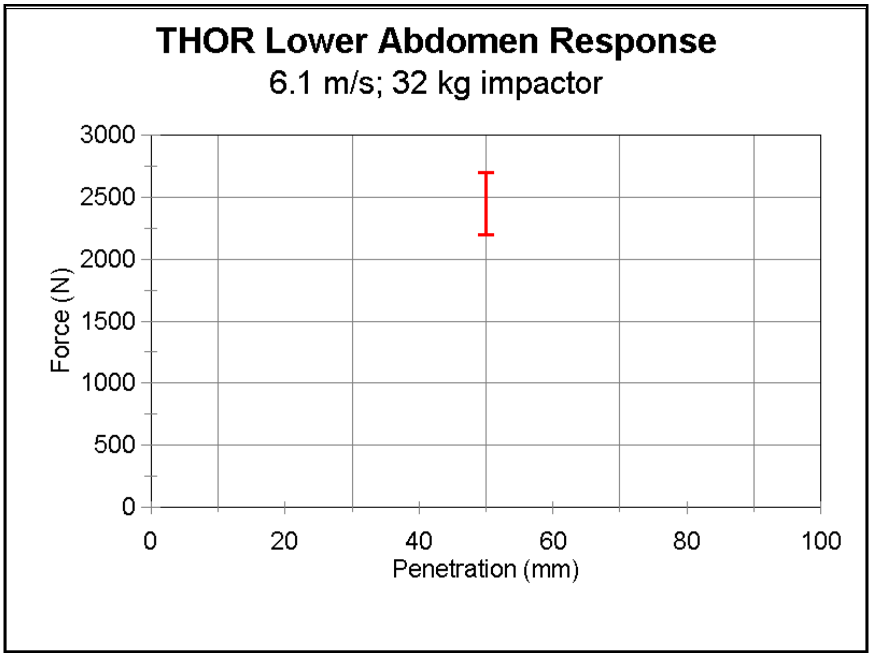


Figure 22. Force response for lower abdomen impact with rigid rod at 6.1 m/s.

6. FEMUR CERTIFICATION

Summary
The standard dynamic test for certifying the response of the Thor femur is the whole body knee impact test at specified initial impact energies [Horsch, 1976].

References

Horsch, J., and Patrick, L. 1976. *Cadaver and Dummy Knee Impact Response.* Proceedings of the 20th Stapp Car Crash Conference. SAE Paper # 760799.

6.1 Knee Impact Tests

Description

This test examines the response of the femur to axial impacts at the knee. The test uses a whole dummy seated in a chair. Peak impactor force and impact velocity are recorded to find whether the force-initial impact energy is within the corridor.

Test Set-up

The parts required for performing the knee impact test are:

1. Fully assembled Thor dummy
2. Impact fixture: either impact pendulum or linear impactor with appropriate mass and velocity.

Instrumentation

The required instrumentation for this test is:

1. Instrumentation to measure impact force (impact accelerometer on impactor or load cell / accelerometer combination)
2. Uniaxial accelerometer attached to femur, distal to the compliant femur element. The accelerometer should measure positive in the direction of impact.
3. Instrumentation to measure the initial impact velocity.

The polarity conventions and data acquisition system must conform to requirements of the 1996 revision of SAE Recommended Practice J211. The impactor load cell and accelerometer should be filtered with CFC 600. Suggested sampling rates for the A/D conversion is 10ksamples/sec

Test Procedure

1. Inspect the knee skin, knee insert and femur puck for wear, tears, or other damage. Prior to assembly the femur puck should also be inspected for any significant permanent set. A small radial bulge is usual after the femur puck has been in service for some time.
2. Soak the dummy in a controlled environment at a temperature between 69° and 72°F overnight prior to testing. The test environment should have the same temperature as the soak environment.
3. The dummy is seated on a horizontal, flat, rigid surface, with the lower legs placed over the edge of the surface, flexed at an angle of 20° from vertical. The torso is unsupported and the arms may be placed along the side of the body.
4. The impactor is rigid with a diameter of 76 mm and mass of 5 kg.
5. The impactor is aligned with the center of the knee, such that it is collinear with the femur axis.
6. Impact velocities are at 1.5 m/s and 2.5 m/s.
7 The impact force is measured and the normal certification procedure will be to determine the peak force for each of the impact velocities.

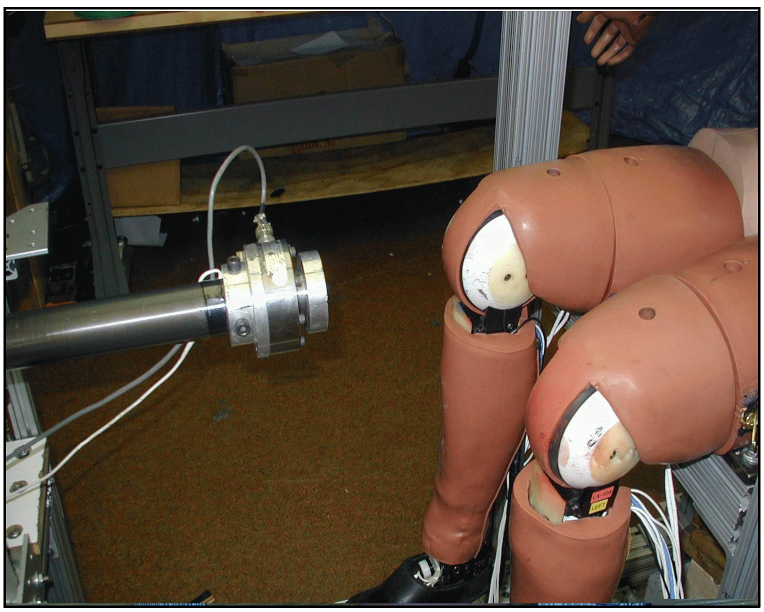


Figure 23. Setup for performing whole body knee impact.

Data Processing

The impactor can either be a pendulum or a linear impactor with the desired mass and geometry. The measurements include:

1. Impact force at the contact face: This can be measured in either of two ways:

    1. With a single linear accelerometer along the line of impact

2. With an in-line load cell measuring axial force and a linear accelerometer along the line of impact. In this case, the mass in front of the load cell, including half the load cell mass should be recorded to determine the inertial correction to the load cell reading. The impact force is given by:

$$F_i = -F_{LC} + m_f a$$

where: F_{LC} = load cell measurement
m_f = mass in front of load cell
a = impactor acceleration

3. Initial impact energy: based on the procedure by Horsch and Patrick:

The method developed by Horsch and Patrick for analyzing knee impacts, involved the calculation of the initial impact energy.

A new independent variable, termed the effective impact energy, is defined:

$$E_e = m_p\, m_s/(m_p + m_s).v^2/2g$$

where: v = impact speed
m_p = mass of pendulum
m_s = effective mass of femur

This variable will be termed the effective impact energy. The term $m_p\, m_s/(m_p + m_s)$ is the reduced mass of a two mass system, consisting of the impactor and the mass of the femur involved during the contact.

The effective femur mass is determined by fitting a straight line to the force vs acceleration curve generated from the knee impact. Only the section of the curve where both the force and the femur acceleration are increasing (from zero to maximum of the acceleration) should be used for fitting the straight line. Thus:

$$F_{knee} = m_s.a_{leg}$$

where: F_{knee} = impact force measured at knee
a_{leg} = acceleration measured on leg
m_s = effective subject mass

Performance Specifications

Table 8. Knee impact response requirement

Effective initial energy (kgm)	Force (N)
0.28 - 0.42	1640 - 2220
0.72 - 1.08	3740 - 5060

Table 9. Knee impact response corridor

	Effective initial energy (kgm)	Force (N)
Upper limit	0.0378	558
	0.9467	6270
Lower limit	0.0322	163
	0.4926	2254

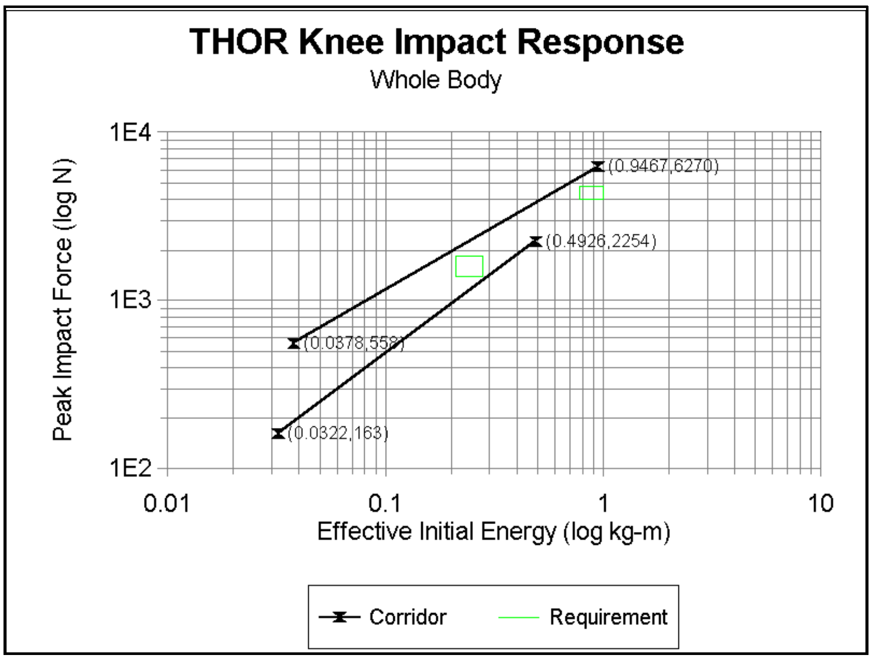


Figure 24. Knee impact response in whole body configuration for varying impactor mass and velocity.

7. FACE CERTIFICATION

Summary

There are two standard dynamic tests for certifying the response of the Thor face. The first is an impact test with a rigid rod at 3.6 m/s, and the second is an impact test with a 150 mm rigid disk at 6.7 m/s [Melvin, 1988].

References

Melvin, J., and Shee, T. 1989. *Facial Injury Assessment Techniques.* Proceedings of the 12th International Conference on Experimental Safety Vehicles.

7.1 Rigid Bar Impact

Description

This test examines the response of the face to impact load across a strip located horizontally below the eyes.

Test Set-up

The parts required for performing the rod impact test are:

1. Fully assembled Thor dummy
2. Impact fixture: either impact pendulum or linear impactor with appropriate mass and velocity.

Instrumentation

The required instrumentation for this test is:

1 Instrumentation to measure impact force (impact accelerometer on impactor or load cell / accelerometer combination)
2 Instrumentation to measure the initial impact velocity.

The polarity conventions and data acquisition system must conform to requirements of the 1996 revision of SAE Recommended Practice J211. The impactor load cell and accelerometer should be filtered with CFC 600. Suggested sampling rates for the A/D conversion is 10ksamples/sec

Test Procedure

For the rod impact test to the face, the configuration is defined as:

1. Inspect the face skin, the face foam, and the head skin for wear, tears, or other damage.
2. Soak the dummy in a controlled environment at a temperature between 69° and 72°F overnight prior to testing. The test environment should have the same temperature as the soak environment.
3. The torso of the subject is maintained straight and the head vertical, with the legs kept horizontal and arms raised. The dummy is seated on a horizontal, flat, rigid surface and is left unsupported at the back.
4. The impactor assembly, including the rod, has a total mass of 32 kg.
5. The cylindrical impactor is rigid with a diameter of 25 mm and length of 30 cm.
6. The rod is configured to impact along the mid-line of the left and right maxilla plates on face.
7. Impact velocity is at 3.6 m/s.
8. The impact force is measured and the normal certification procedure will be to determine the peak force and the time at which peak force is reached.

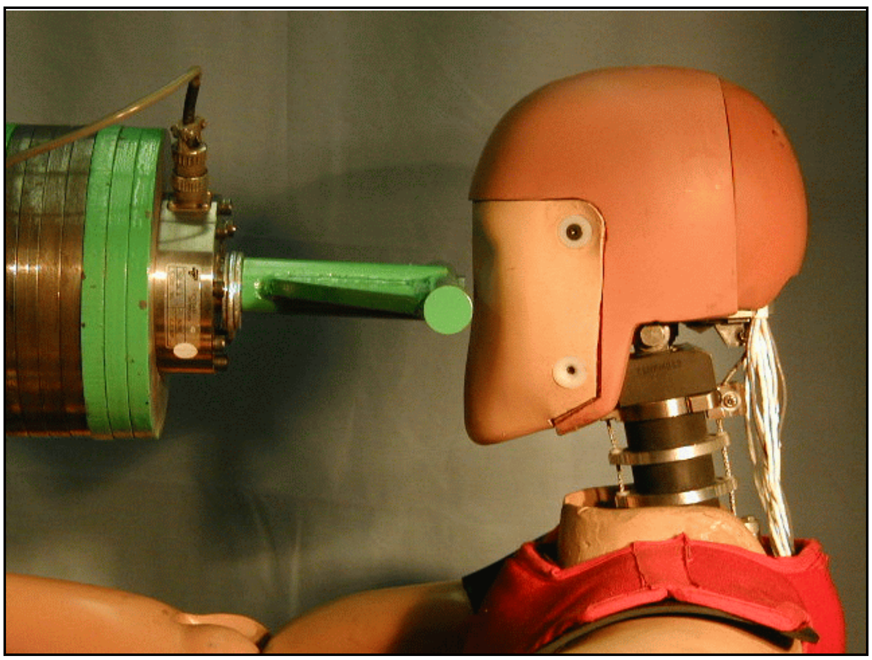


Figure 25. Setup of face impact test with rigid rod.

Data Processing

The impactor can either be a pendulum or a linear impactor with the desired mass and geometry. The measurements include:

1. Impact force at the contact face: This can be measured in either of two ways:
    1. With a single linear accelerometer along the line of impact
    2. With an in-line load cell measuring axial force and a linear accelerometer along the line of impact. In this case, the mass in front of the load cell, including half

the load cell mass should be recorded to determine the inertial correction to the load cell reading. The impact force is given by:

$$F_i = -F_{LC} + m_f a$$

where: F_{LC} = load cell measurement
m_f = mass in front of load cell
a = impactor acceleration

Performance Specifications

The specification for the face impact with rigid rod is given by:

Peak force:	2470 - 3020 N
Time for peak force:	8 - 10 msec

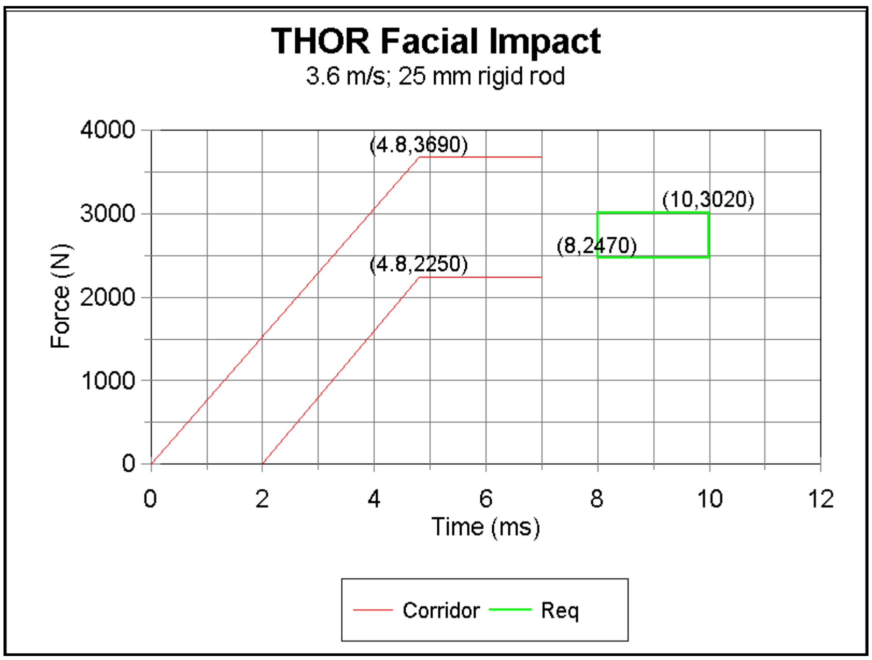


Figure 26. Force vs. time response for facial impact with rigid rod

7.2 Rigid Disk Impact

Description

This test examines the response of the face to a distributed load across the whole face. The test is performed using a disk impactor with a diameter of 152 mm and mass of 13 kg.

Materials

The parts required for performing the disk impact test are:

1. Fully assembled Thor dummy
2. Impact fixture: either impact pendulum or linear impactor with appropriate mass and velocity.

Instrumentation

The required instrumentation for this test is:

1. Instrumentation to measure impact force (impact accelerometer on impactor or load cell / accelerometer combination)
2. Instrumentation to measure the initial impact velocity.

The polarity conventions and data acquisition system must conform to requirements of the 1996 revision of SAE Recommended Practice J211. The impactor load cell and accelerometer should be filtered with CFC 600. Suggested sampling rates for the A/D conversion is 10ksamples/sec

Test Procedure

For the disk impact test to the face, the configuration is defined as:

1. Inspect the face skin, the face foam, and the head skin for wear, tears, or other damage.
2. Soak the dummy in a controlled environment at a temperature between 69° and 72°F overnight prior to testing. The test environment should have the same temperature as the soak environment.
3. The torso of the subject is maintained straight and the head vertical, with the legs kept horizontal and arms raised. The dummy is seated on a horizontal, flat, rigid surface and is left unsupported at the back.
4. The impactor assembly, including the disk, has a total mass of 13 kg.
5. The disk impactor is rigid with a diameter of 150 mm, with an edge radius of 12 mm.
6. The center of the disk is configured to impact at the mid-point of the line joining the two maxilla plates on the face.
7. Impact velocity is at 6.7 m/s.
8. The impact force is measured and the normal certification procedure will be to determine the peak force and the time at which peak force is reached.

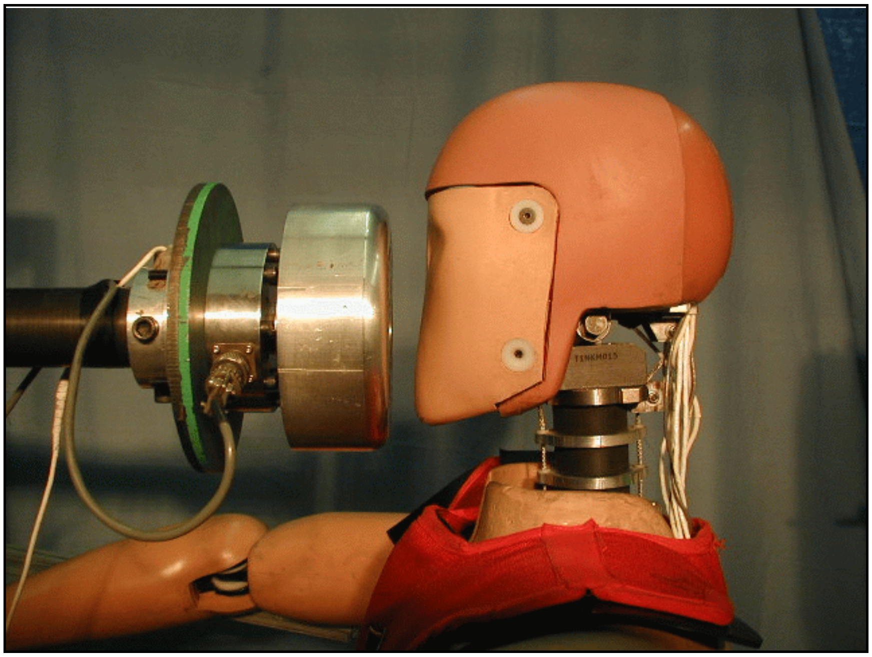


Figure 27. Setup for face impact test with rigid disk.

Data Processing

The impactor can either be a pendulum or a linear impactor with the desired mass and geometry. The measurements include:

1. Impact force at the contact face: This can be measured in either of two ways:
    1. With a single linear accelerometer along the line of impact
    2. With an in-line load cell measuring axial force and a linear accelerometer along the line of impact. In this case, the mass in front of the load cell, including half the load cell mass should be recorded to determine the inertial correction to the load cell reading. The impact force is given by:

$$F_i = -F_{LC} + m_f a$$

where: F_{LC} = load cell measurement
m_f = mass in front of load cell
a = impactor acceleration

Performance Specifications

The specification for the face impact with rigid disk is given by:

Peak force:	8325 - 9675 N
Time for peak force:	3.8 - 5.0 msec

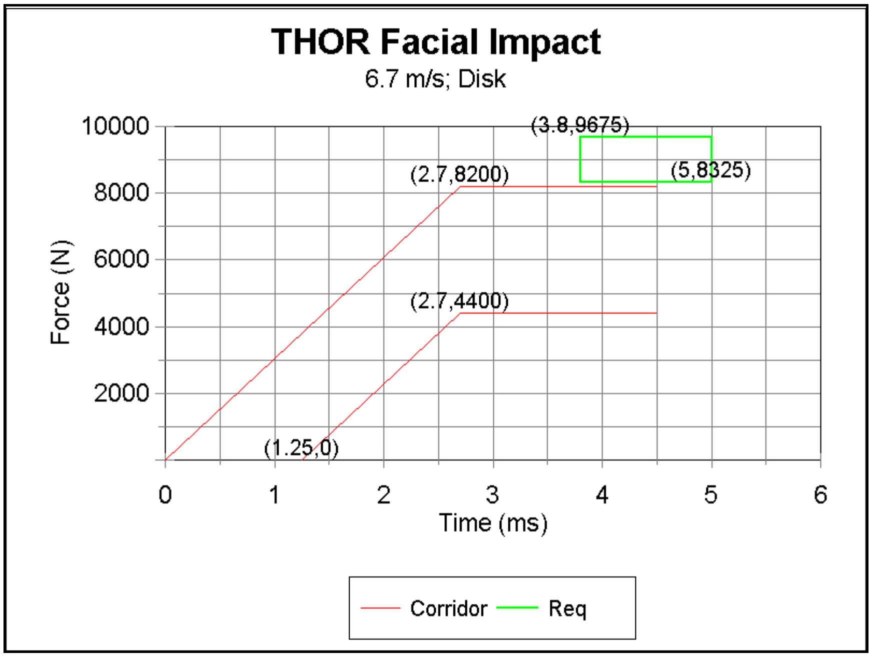


Figure 28. Force vs. time response for facial impact with rigid disk.

8. LOWER LEG/ANKLE/FOOT CERTIFICATION

Summary

The certification tests for the lower leg assembly include quasi-static ankle motion in inversion and eversion, and impacts to the ball and heel of the foot. Detailed description of the certification procedures are given in the document: ***Certification Procedures for the Thor-LX/Hybrid III Retrofit Version 3.0-December, 2000***. Most of the description in the above document is reproduced here to make this certification document complete.

There are a number of quasi-static tests that are used for the purposes of design reference guidance and are described in Section II. These include quasi-static dorsiflexion and plantarflexion, compression testing on the materials used in the ankle stops, and on the spring used in the Achilles tube.

Reference

VRTC. 2000. *Certification Procedures for the Thor-LX/Hybrid III Retrofit Version 3.0-December, 2000*

8.1 Quasi-static Inversion and EversionTests

Description

The quasi-static inversion and eversion tests examine the range of motion and resistance of the ankle joint soft stops in inversion and eversion.

Materials

The equipment and fixtures utilized in this test are:

1. Machine capable of vertical travel with application of load (e.g. Universal Testing Machine)
2. Steel cable
3. Rigid fixture to horizontally mount lower leg to universal testing machine
4. Ankle Moment Arm
5. Cable Attachment Bracket
6. Lower leg/ankle/foot assembly below the compressible tibia element.

Instrumentation

The instrumentation required for the quasi-static tests is:

1. Lower leg assembly including the following parts, ankle assembly, Achilles assembly, tibia assembly, and X, Y, and Z-axis rotary potentiometers.
2. Instrument to measure moment and force.

Test Procedure

1. Inspect the dorsiflexion/plantarflexion and inversion/eversion soft stop assemblies for uneven wear, tears, or other damage. Check for smooth rotation of the ankle about all three axes.
2. Soak the ankle, foot, and tibia assemblies in a controlled environment at a temperature between 69 °F and 72 °F for at least four hours prior to testing. The test environment should have the same temperature as the soak environment.
3. Rigidly mount the tibia and align the foot at zero position (0° dorsiflexion, plantarflexion, inversion, and eversion, 0° rotation about Z-axis).
   Since the lower leg naturally rests at 15° plantarflexion, an external device will be necessary to hold the foot at 0° plantarflexion for the inversion/eversion tests. (Note: Rotation about the Z-axis is undesirable during the quasi-static tests and should be prevented.)
4. Do not attach the tendon during the testing. Also, the potentiometer channels should be set according to calibration values provided by the manufacturer and verified for accuracy.
5. Rotate the ankle from the initial starting position to 37-38° inversion or eversion at a rate of 1-2°/second. (Note: Do not rotate beyond 38° to avoid damage as this angle is near the joint mechanical limit.)
6. Calculate the torque at the ankle joint.

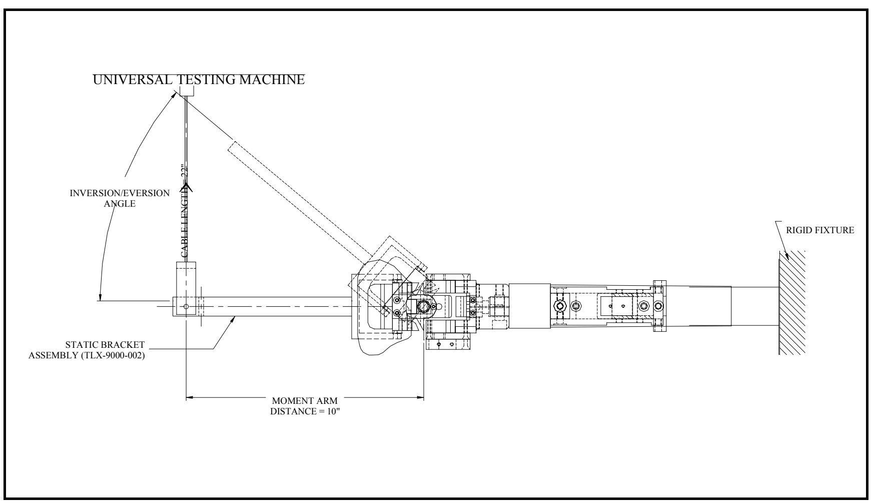


Figure 29. Setup for quasi-static inversion/eversion test of Thor lower leg.

Data Processing

The polarity conventions must conform to requirements of the 1996 revision of SAE Recommended Practice J211. The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

The torque at the ankle joint is determined as follows (referring to Figure 30):

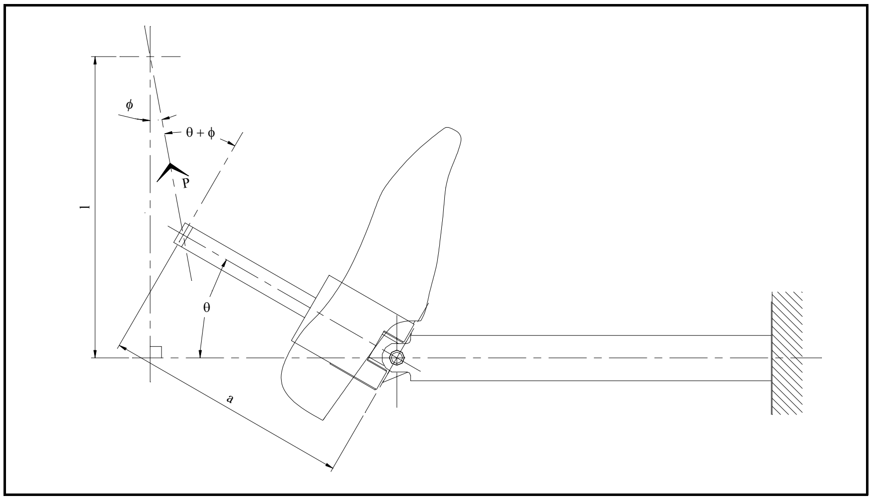


Figure 30. Setup for calculation procedure.

The angle made by the cable to the vertical is first computed:

$$\sin\phi = \frac{a - a\cos\phi}{l}$$

$$\phi = \sin^{-1}\left(\frac{a - a\cos\phi}{l}\right)$$

where: a = length of arm between cable attachment point and point of rotation
l = length of cable between attachment point on foot and to attachment point on load platform
ϕ = angle made by cable with vertical

The effective moment acting about the joint is then:

$$T = Fa\cos(\theta + \phi)$$

where: T = torque acting about ankle joint
F = force measured by load cell attached to cable

Performance Specifications

The angle at which the following torque values are measured should be within the corresponding ranges:

Inversion/Eversion	6 N.m:	17.5 - 21.3°
	23 N.m:	29.3 - 35.9°

The relative location of the certification specifications relative to the original biomechanical specifications are shown in the following graphs.

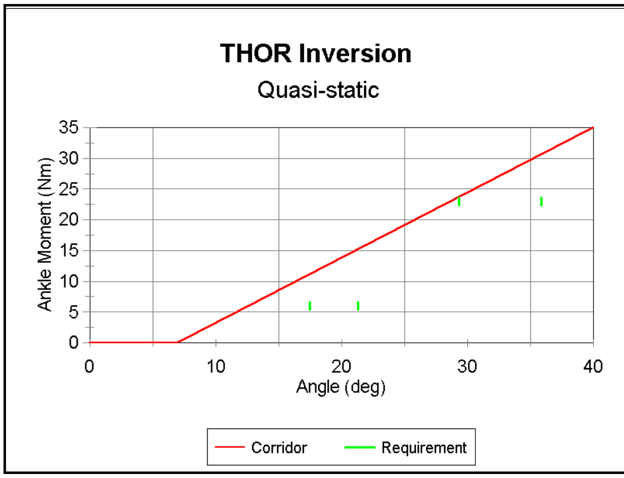


Figure 31. Quasi-static inversion response.

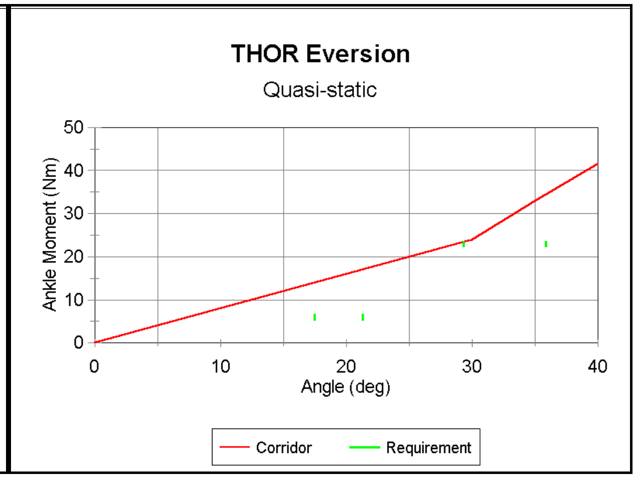


Figure 32. Quasi-static eversion response.

8.2 Dynamic Dorsiflexion Test

Description

This dynamic impact test validates the performance of the ankle and the compliant elements in the foot and tibia. The anatomical areas of pendulum impact are the ball of foot. The test velocity is 5.0 m/s.

Materials

The required parts for this test are:

1. NHTSA Dynamic Impactor (described in VRTC document: Certification Procedures for the Thor-LX/Hybrid III Retrofit Version 3.0). The combined mass of the impactor face, ballast, and 1/3 of the supporting tube is 5kg. Because the densities and weights of some materials may vary, slight adjustment of the dimensions may be needed to achieve the same 5kg mass. The supporting structure for the NHTSA Dynamic Impactor is determined by the test facility.
2. Tibia Mounting Fixture
3. Lower leg/ankle/foot assembly below compressible tibia element.

The setup for the test is shown in the following figure.

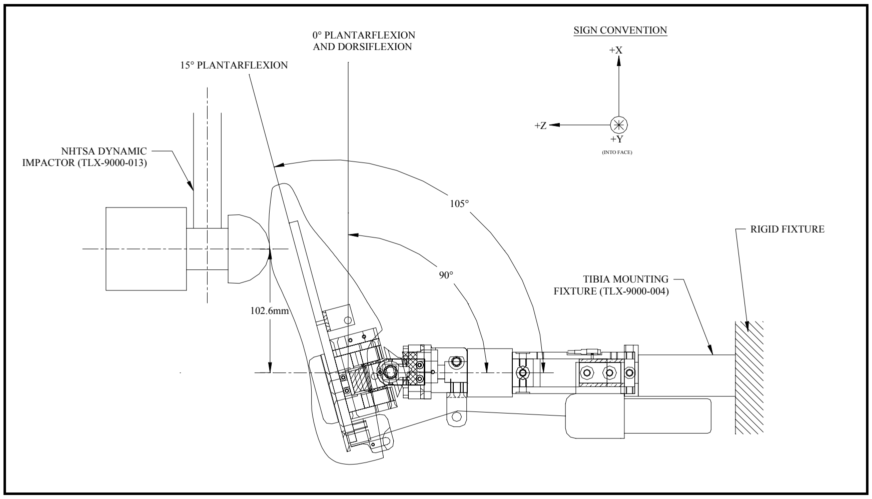


Figure 33. Setup of pendulum fixture for dynamic dorsiflexion test.

Instrumentation

The instrumentations used for this test is:

1. Lower leg assembly, including foot assembly, ankle assembly, tibia assembly, Achilles assembly, five channel lower tibia load cell , four channel upper tibia load cell (heel of foot test only), and X, Y, and Z- axis ankle rotary potentiometers
2. Instrumentation to measure impactor velocity

Test Procedure

1. Inspect the ankle soft stops for tears, permanent deformations, or separation from the soft stop brackets. Inspect the foot skin for wear and tears.
2. Soak the ankle, foot, and tibia assemblies in a controlled environment at a temperature between 69°F and 72°F for at least four hours prior to a test. The test environment should have the same temperature as the soak environment.
3. Remove the Tibia Compliant Bushing Assembly and mount the leg to the Tibia Mounting Fixture at the lower flange, with the toe pointing upward. The test fixture must be rigidly secured so that it does not move during impact.
4. Verify that the Achilles spring cable tension is correctly adjusted. (See Thor-Lx/HIIIr User's Manual).
5. Allow the foot to rest in neutral position (15° plantarflexion, 0° inversion and eversion, 0° rotation about the Z-axis) and zero all instrumentation channels except the rotary potentiometers. Potentiometer channels should be set according to calibration values provided by the manufacturer and verified for accuracy (See Thor-Lx/HIIIr User's Manual). Leave the foot in neutral position for impact.
6. Adjust the fixture so that the longitudinal centerline of the pendulum arm is vertical at impact, and the point of impact is 102.6 mm (4.04 in) above the ankle Y-axis pivot point.

7. Release the pendulum and allow it to fall freely from a height to achieve an impact velocity of 5 ± 0.1 m/s (16.4 ± 0.3 ft/s). Time-zero is defined as the time of initial contact between the pendulum impactor and the ball of the foot.
8. Record data from the following channels:
   Lower Tibia Load Cell - Fx, Fy, Fz, Mx, My
   X, Y, Z-axis Rotary Potentiometers
   Pendulum acceleration
9. Wait at least 30 minutes between successive impacts to the same foot.

Data Processing

The polarity conventions and data acquisition system must conform to requirements of the 1996 revision of SAE Recommended Practice J211. The lower tibia load cell and accelerometer should be filtered with CFC 600. The rotary potentiometers should be filtered at CFC 180. Suggested sampling rates for the A/D conversion is 10 ksamples/sec

The ankle moment is computed using the formula:

$$M_{ankle} = M_y - aF_x$$

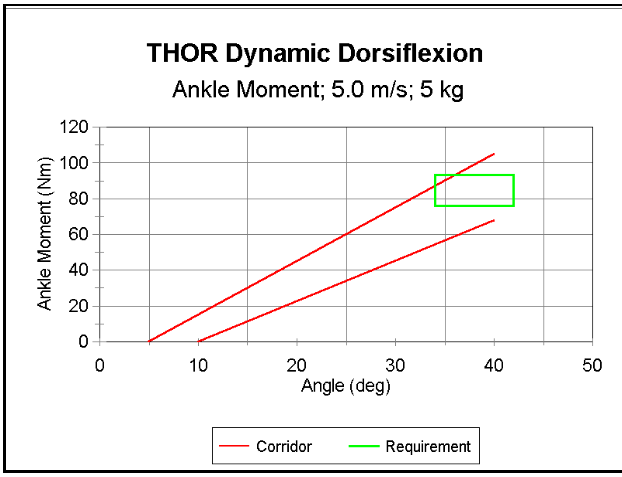
where:
- M_y = moment about Y-axis measured by lower tibia load cell
- F_x = force along X-axis measured by lower tibia load cell
- a = distance between center of lower tibia load cell and dorsiflexion joint (.0907m)

The angle is measured with the Y rotary potentiometer. The appropriate offset should be subtracted so that when the foot is perpendicular to the tibia, the angle is computed as zero.

Performance Specification

The certification corridors for the ball of foot impact tests are defined as follows.
Peak Lower Tibia Compressive Force 3058 - 3738 N
Peak Ankle Resistive Moment 76.2 - 93.2 Nm

The corridors are shown in the following graphs. For the ankle moment, the corridor is compared with the biomechanical response requirements.



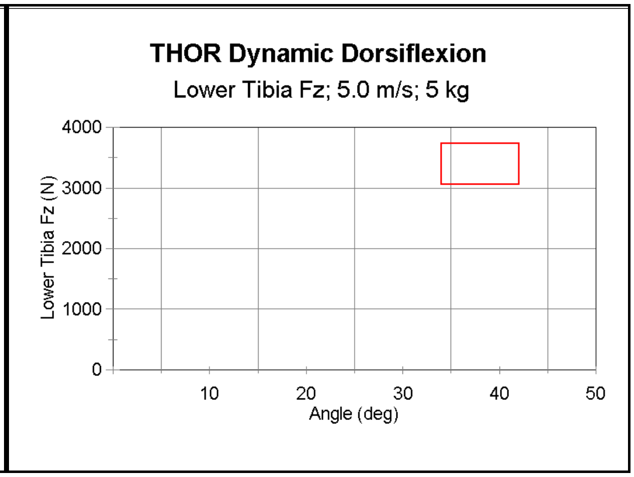


Figure 34. Peak ankle moment response for dynamic dorsiflexion.

Figure 35. Peak lower tibia Fz response for dynamic dorsiflexion.

8.3 Dynamic Heel Impact Test

Description

This dynamic impact test validates the performance of the ankle and the compliant elements in the foot and tibia. The anatomical areas of pendulum impact are the heel of foot. The test velocity is 4.0 m/s.

Materials

The required fixture for this test is:

NHTSA Dynamic Impactor (see Dynamic Dorsiflexion)). The combined mass of the impactor face, ballast, and 1/3 of the supporting tube is 5kg (11 lbs). Because the densities and weights of some materials may vary, slight adjustment of the dimensions may be needed to achieve the same 5kg (11 lbs) mass. The supporting structure for the NHTSA Dynamic Impactor is determined by the test facility.

The setup of the test is shown in the following figure.

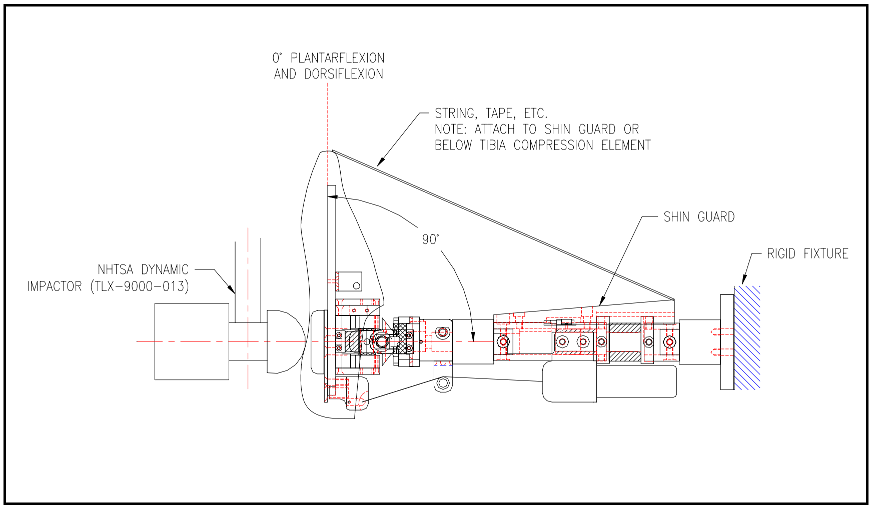


Figure 36. Setup of impact pendulum for dynamic heel impact test.

Instrumentation

The instrumentations used for this test are:

1. Lower leg assembly, including foot assembly, ankle assembly, tibia assembly, Achilles assembly, five channel lower tibia load cell , four channel upper tibia load cell (heel of foot test only), and X, Y, and Z- axis ankle rotary potentiometers
2. Instrumentation to measure impactor velocity

Test Procedure

1. Soak the ankle, foot, and tibia assemblies in a controlled environment at a temperature between 69° and 72° F for at least four hours prior to a test. The test environment should have the same temperature as the soak environment.
2. Inspect the tibia compliant bushing assembly for fatigue and deformation. Check the plunger retaining bolts for wear.
3. Remove the knee clevis and mount the tibia to the test fixture at the proximal end of the upper tibia load cell with the toe pointing upward. The test fixture must be rigidly secured so that it does not move during impact.
4. Zero the instrumentation channels, excluding the rotary potentiometers, with the foot resting in neutral position (15° plantarflexion, 0° inversion and eversion, 0° rotation about the Z-axis). Rotary potentiometer channels should be set according to the calibration sheets provided by the manufacturer and verified for accuracy. (See Thor-Lx/HIIIr User's Manual)
5. Impact the heel at 0° plantarflexion. A piece of tape, string, or wire, etc. extending from the toe to the shin guard or another area below the tibia compressive element will be required to hold the foot at this position. (Note: Attaching the tape, string, etc. to areas on the leg proximal to the tibia compressive element may significantly alter the foot from 0° plantarflexion during heel impact and is not desirable).

6. Adjust the fixture so that the longitudinal centerline of the pendulum arm is vertical at impact, and the impact point is aligned with the tibia centerline.
7. Release the pendulum and allow it to fall freely from a height to achieve an initial impact velocity of 4 ± 0.1 m/s (13.1 ± 0.3 ft/s). Time-zero is defined as the time of initial contact between the pendulum impactor and the heel of the foot.
8. Record the following data channels.
   Lower Tibia Load Cell - Fx, Fy, Fz, Mx, My
   Upper Tibia Load Cell - Fx, Fz, Mx, My
   X, Y, Z-axis Rotary Potentiometers
9. Wait at least 30 minutes between successive impacts to the same foot.

Performance Specification

The peak compressive force measured by the lower tibia load cell should be within the range of 2694 - 3292 N. The performance requirement is shown in the following graph along with the original biomechanical requirement.

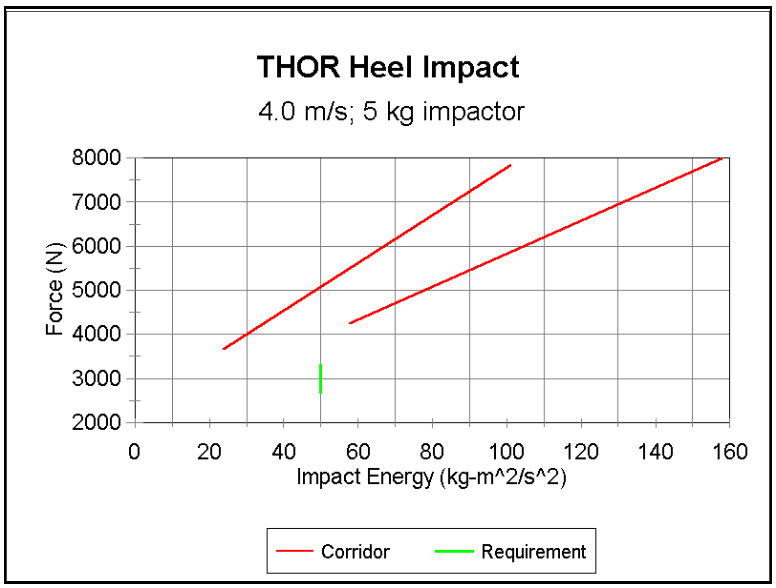


Figure 37. Peak lower tibia Fz under dynamic heel impact.

SECTION II. DESIGN REFERENCE TESTS

The following sections describe tests currently performed on selected components of Thor to provide a comparison to design reference values. Majority of the tests are quasi-static compression tests which are performed on the deformable materials used in Thor. The response range provided can be used as a design guide for acceptance or rejection of the material. It should be emphasized that these tests are meant as a guide only, and the actual performance requirements of the Thor components will depend on the responses described in Section I of this document. In addition to compression tests, there are number of additional tests that can be used to evaluate the performance of the Thor neck, thoracic and lumbar flex joints, and the ankle joints, after the units have been molded and assembled. Once again, the actual performance requirement depend on the response in a dynamic environment, but response within the limits provided here will generally make it likely that the unit will perform properly under dynamic loads.

9. NECK

9.1 Neck Quasi-static Puck Material Compression Test

Description

The neck material (Neoprene 75A) compression test is a quasi-static test designed to check the force-deflection characteristics of the material for the specific geometry of the neck pucks. The results from the test are used to compare with the design reference as given in the Thor-Alpha Drawing Package (Version 1.0). The manufacturer can use the information to aid in the final neck assembly.

Materials

The parts required for the material compression test are:

1. Single, solid neck puck (with elliptical geometry -56.1 mm x 71.4 mm x 19.0 mm)
2. Any test equipment capable of applying compressive load quasi-statically (e.g. Universal Test Machine).

Instrumentation

The required instrumentation for this test is:

1. Compression Load Cell (minimum capacity 12000 N)
2. Displacement transducer (e.g. LVDT)

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the neck puck material for wear, tears, or other damage.
2. Soak the puck in a controlled environment at a temperature between 69° and 72°F for at least 30 minutes prior to testing. The test environment should have the same temperature as the soak environment.
3. Rest the neck puck on a flat base plate rigidly attached to the test fixture. The loading plate should also be flat. Both the base plate and the loading plate should have a larger area than the specimen. The specimen should be free to slip at both the lower and upper surfaces.
4. Slowly compress the specimen at a rate of 1 - 5 mm /sec, until about 50% compression is achieved.
5. Measure the compression force using the load cell and the displacement with the displacement transducer.

Performance Specifications

Determine the compression force for compressions of 25% and 50%. The compression corridor is specified as:

Load for 40% compression (at 7.6 mm): 13200 - 14650 N

Typical force-deflection response from the compression test is shown in the graph below.

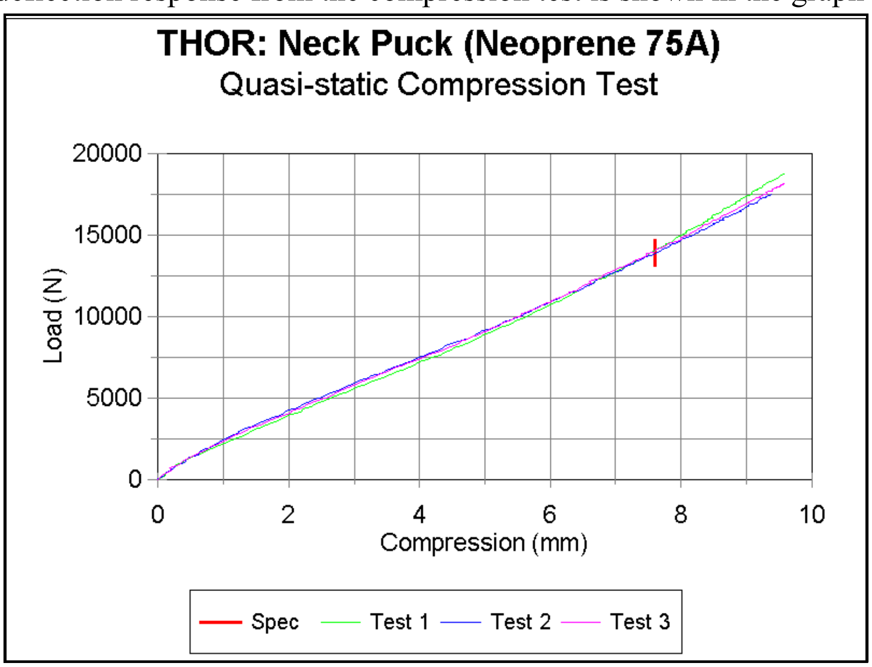


Figure 38. Force-deflection response for single neck puck in quasi-static compression.

9.2 Neck Front/rear Spring Quasi-static Compression Test

Description

This test is a quasi-static test designed to check the force-deflection characteristic of the neck front and rear springs. The result from the test is used to compare with the design reference as given in the Thor-Alpha Drawing Package (Version 1.0; Drawing T1xxxxxx). The manufacturer can use the information to aid in the final neck assembly.

Materials

The parts required for the material compression test are:

1. Neck front and rear spring (with standard geometry). The front spring should be tested by itself and when the Viton 75A tube is inserted into it.
2. Any test equipment capable of applying compressive load quasi-statically (e.g. Universal Test Machine).

Instrumentation

The required instrumentation for this test is:

1. Compression Load Cell (minimum capacity 2000 N)
2. Displacement transducer (e.g. LVDT)

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the neck front/rear spring for any damage or for permanent set. Check the Viton for any wear or tears.
2. Mount the spring to a flat, base plate attached to the test fixture. The spring can be retained in a holder, such that sufficient length is exposed for compression. The loading plate should be flat and its area should be larger than that of the spring. The specimen should be free to slip at both the lower and upper surfaces.
3. Slowly compress the spring at a rate of 1 - 5 mm /sec.
4. Measure the compression force using the load cell and the displacement with the displacement transducer.

Performance Specifications

The force-deflection corridors for the front and rear spring are specified as:

Front Spring:

Force at 30 mm compression - spring only: 250 - 290 N

Force at 30 mm compression - spring+Viton: 810 - 925 N
Maximum compressible length: > 32.5 mm

Rear Spring:
Force at 30 mm compression: 820-900 N
Maximum compressible length: > 35 mm

Typical force-deflection response from the compression test is shown in the graphs below.

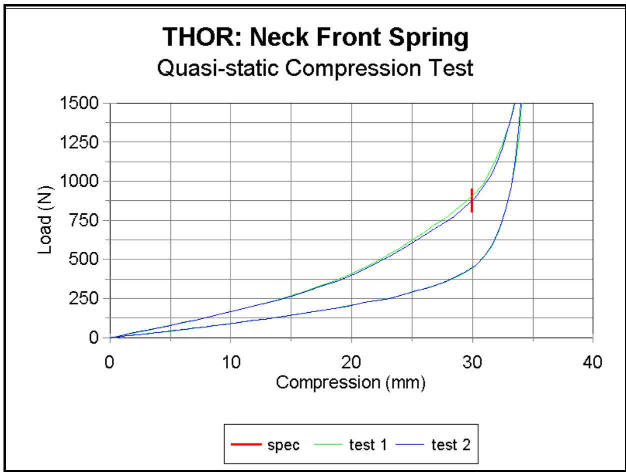


Figure 39. Force-deflection response for quasi-static compression of neck front spring + Viton.

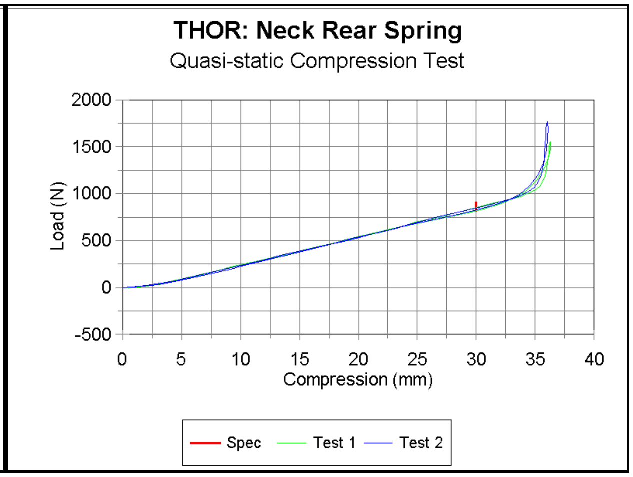


Figure 40. Force-deflection response for quasi-static compression of neck rear spring.

9.3 Quasi-static Flexion Tests

Description

The quasi-static tests of the neck, in frontal flexion, lateral flexion, and extension are used to measure the quasi-static moment-angle response of the Thor neck under these motions. The user can utilize this information to aid in evaluating the performance of the neck.

Materials

The parts required for the frontal flexion test are:

1. Neck assembly
2. Fixture capable of applying moment to the top of the neck assembly under quasi-static loading. A representative system is shown in the figure below.

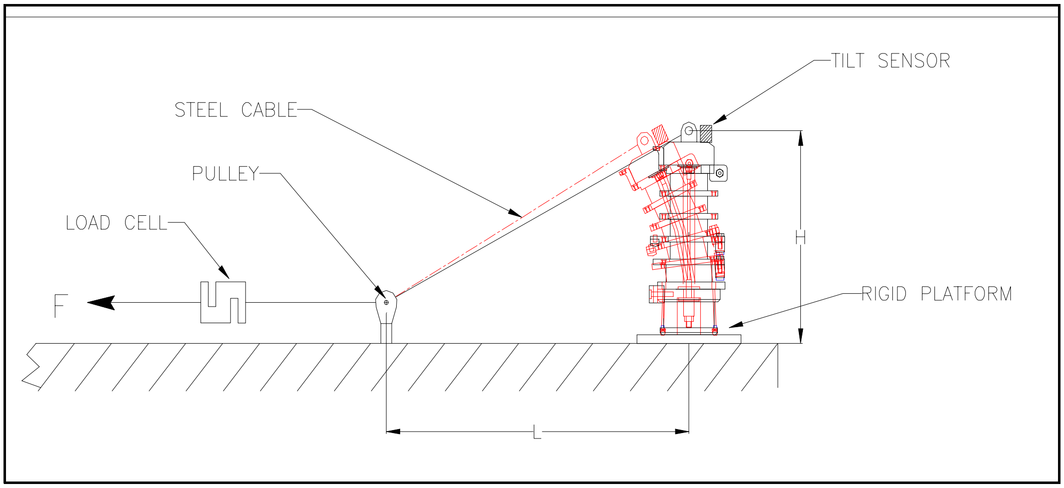


Figure 41. Sketch of fixture for performing quasi-static bending tests of the neck assembly.

Instrumentation

The instrumentation required for the test is:

1. Tension/compression load cell
2. Tilt sensor / inclinometer

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the neck assembly for wear, tears, or other damage and for any debonding between the rubber pucks and metal plates.
2. Soak the neck assembly in a controlled environment at a temperature between 69° and 72°F for at least four hours prior to testing. The test environment should have the same temperature as the soak environment.
3. Mount the neck assembly rigidly to the base plate of the test fixture and then mount the deflection rod to the top plate of the neck assembly. For the frontal flexion test, the assembly is aligned so that the anterior-posterior direction is aligned with the long axis of the fixture. For the lateral flexion test, the neck is placed such that the assembly is rotated 90° relative to long axis of the fixture. For the extension test, the neck is placed such that the anterior-posterior direction of the assembly is rotated 180° relative to long axis of the fixture. Ensure that the initial starting position of the neck is 0° ± 1° .
4. Slowly rotate the top rod from the initial starting position to about 50° at a rate of 1 - 2°/second.
5. Calculate the torque at the center of the neck. Calculation procedure is shown below.

Calculation Procedure

The principal response that is evaluated from the flexion tests, is moment vs. angle. The angle of the top plate of the neck (and of the attached rod) is measured using the tilt sensor or inclinometer. The moment is determined from the force measured in the load cell along the cable running from the top of the neck assembly as seen in Figure 4. The following figure shows the basic geometry used for performing the calculation.

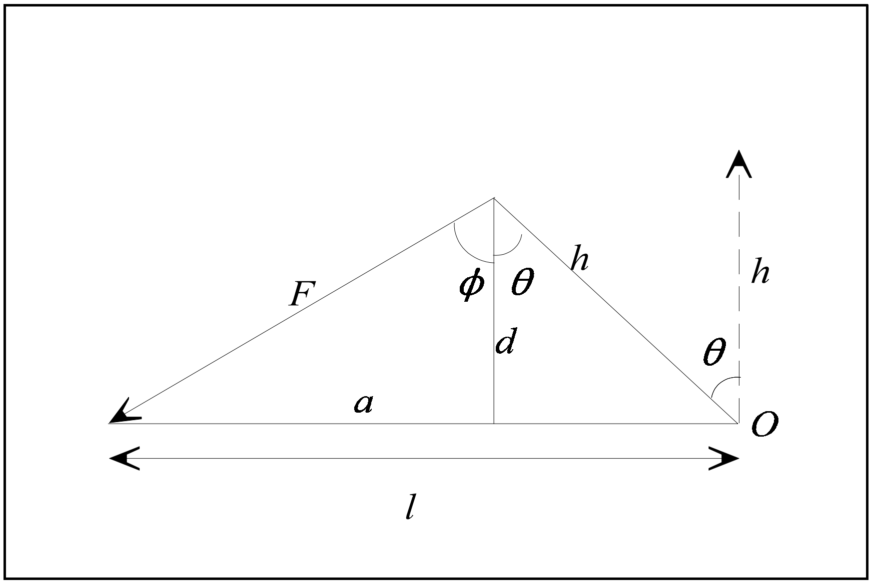


Figure 42. Setup of geometry for performing moment calculations in the bending fixture.

In the above figure, the solid line **h** shows the inclined position of the assembly at angle θ from the vertical, and the line of action of the force on the cable is given by **F**.

The angle ϕ is given by:

$$\phi = atan\left(\frac{a}{d}\right) = atan\left(\frac{l - h\sin\theta}{h\cos\theta}\right)$$

The moment due to force **F** about the base of the assembly **O**, is given by:

$$M = Fh\sin(\theta + \phi)$$

In the above computation, it is assumed that there is negligible change in the length **h** of the assembly, which should hold for the bending angles of interest.

Performance Specifications

Frontal Flexion

Determine the torque for frontal flexion at 45°. The torque certification requirements are as follows:

Frontal Flexion at 45°: 41 - 50 N-m

Typical moment-angle response from the quasi-static frontal flexion test is shown in the graph below.

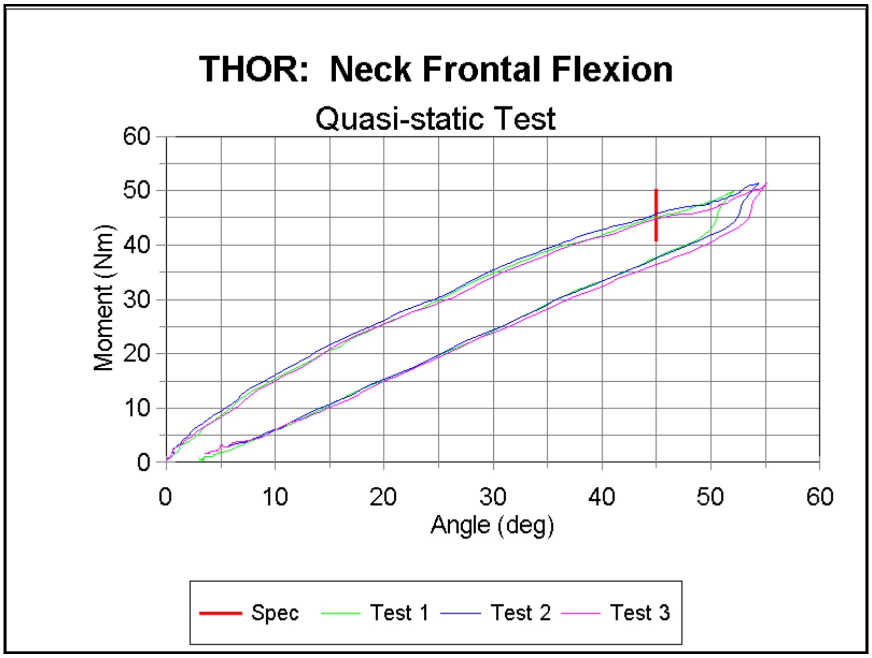


Figure 43. Quasi-static neck frontal flexion requirement

Lateral Flexion

Determine the torque for lateral flexion at 45°. The torque certification requirements are as follows:

Lateral Flexion at 45°: 60 - 67 N-m

Typical moment-angle response from the quasi-static lateral flexion test is shown in the graph below.

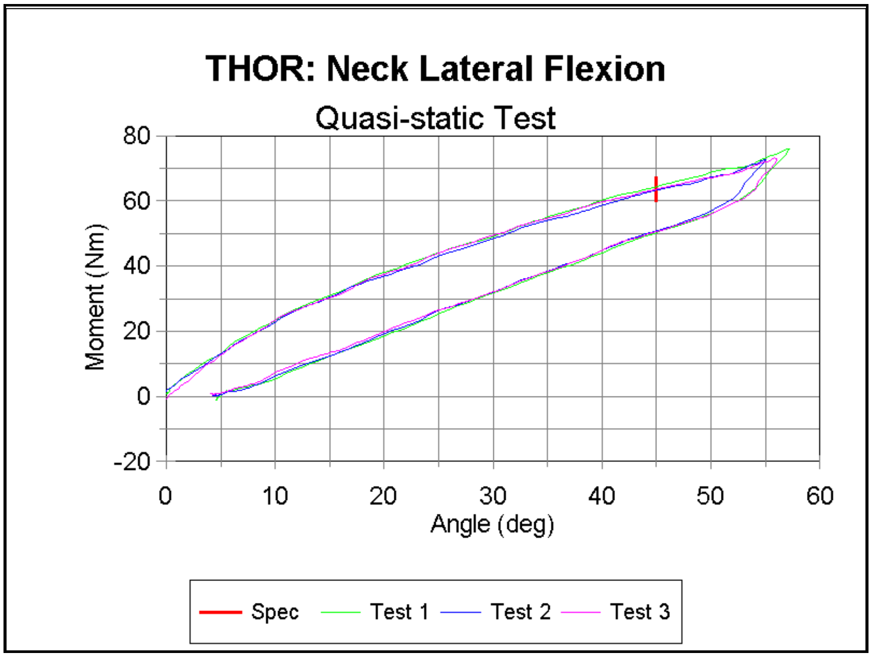


Figure 44. Quasi-static neck lateral flexion requirement.

Extension

Determine the torque for extension at 45°. The torque certification requirements are as follows:

Extension at 45°: 32 - 36 N-m

Typical moment-angle response from the quasi-static extension test is shown in the graph below.

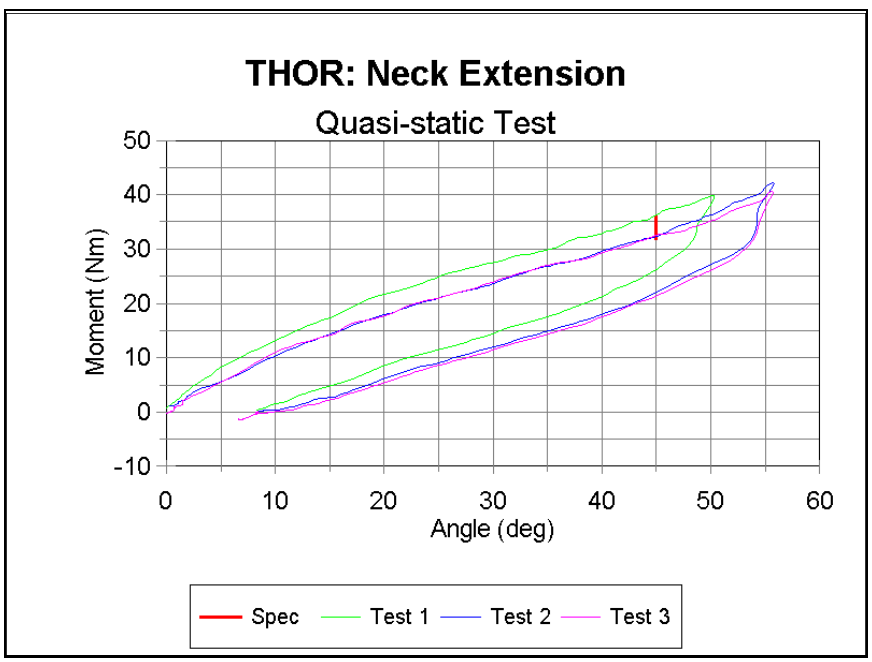


Figure 45. Quasi-static neck extension requirement

10. SPINE

Summary

There are currently no biomechanical targets that have been defined, which the Thor spine has to meet. Instead there is a quasi-static compression test for the material used in the thoracic and lumbar flexion joints. In addition, there are quasi-static flexion responses (in both frontal and lateral directions) that are used as design reference. The references can be used by the manufacturer to aid in the building of the spine assembly.

10.1 Flex Joint Material Compression Test

Description

The flex joint material (Urethane 65A) compression test is a quasi-static test designed to check the force-deflection characteristics of the material for a standard geometry using the material. The results from the test are used to compare with the design reference as given in the Thor-Alpha Drawing Package (Version 1.0). The manufacturer can use the information to aid in the final flex joint assembly. A single test can be used for both the thoracic and lumbar flex joints, since they use the same material.

Materials

The parts required for the material compression test are:

1. A 50.8 mm x 50.8 mm x 50.8 mm (2" x 2" x 2") sample molded using the same formulation used to make the flex joints.
2. Any test equipment capable of applying compressive load quasi-statically (e.g. Universal Test Machine).

Instrumentation

The required instrumentation for this test is:

1. Compression Load Cell (minimum capacity 12000 N)
2. Displacement transducer (e.g. LVDT)

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the material for wear, tears, or other damage.

2. Soak the specimen in a controlled environment at a temperature between 69° and 72°F for at least 30 minutes prior to testing. The test environment should have the same temperature as the soak environment.
3. Rest the sample on a flat base plate rigidly attached to the test fixture. The loading plate should also be flat. Both the base plate and the loading plate should have a larger area than the specimen. The specimen should be free to slip at both the lower and upper surfaces.
4. Slowly compress the specimen at a rate of 1 - 5 mm /sec, until about 50% compression is achieved.
5. Measure the compression force using the load cell and the displacement with the displacement transducer.

Performance Specifications

Determine the compression force for compression of 50%. The compression corridor is specified as:

Force at 50% compression: 10660 - 11780 N

Typical force-deflection response from the compression test is shown in the graph below.

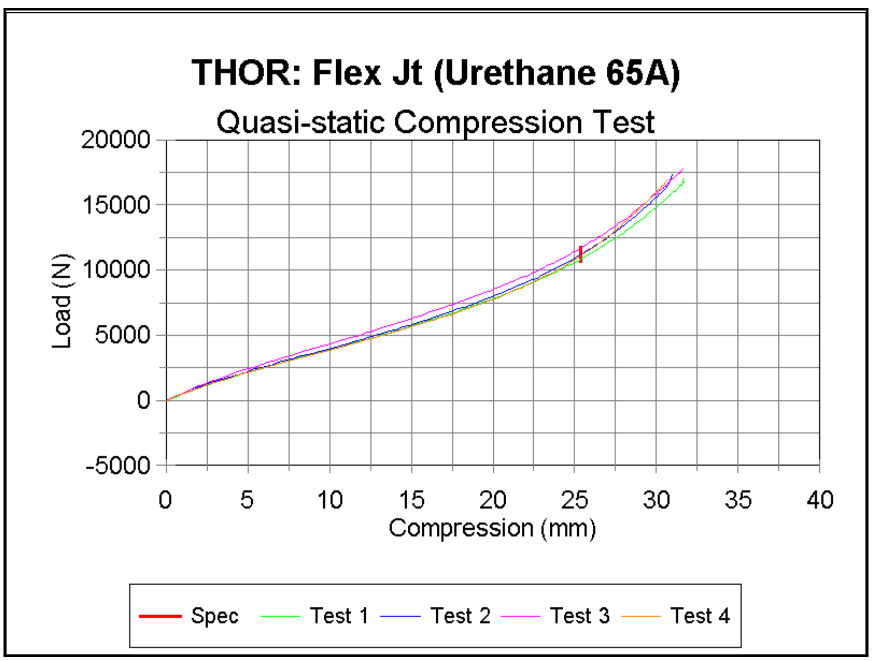


Figure 46. Force-deflection response of flex joint material under quasi-static compression.

10.2 Thoracic Flex Joint Quasi-static Frontal Flexion Test

Description

The static frontal flexion test of the thoracic flex joint is used to measure its quasi-static moment-angle response when bent in the frontal direction.

Materials

The parts required for the frontal flexion test are:

1. Complete thoracic flex assembly
2. Quasi-static bending fixture. A representative fixture is shown in the figure below.

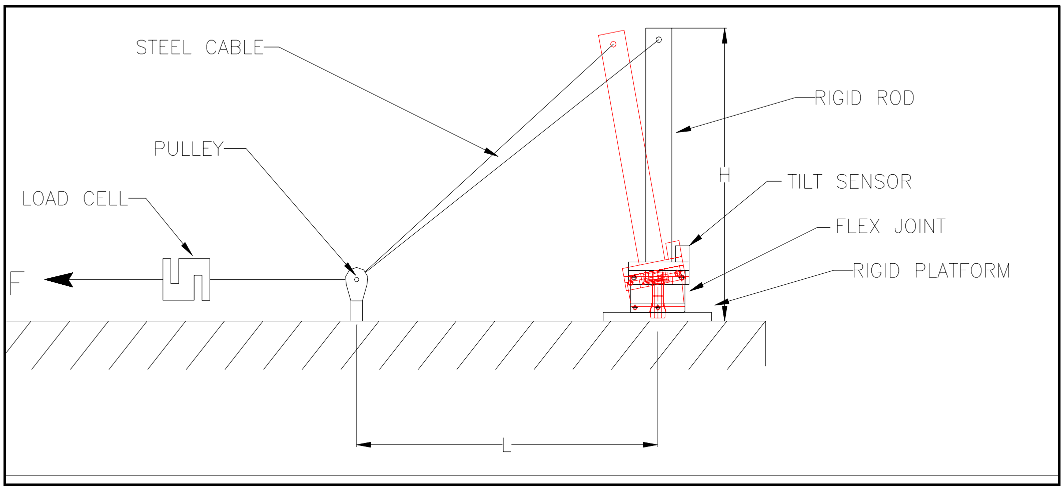


Figure 47. Sketch of fixture for performing quasi-static bending tests with flex joints.

Instrumentation

The instrumentation required for the test is:

1. Tension/compression load cell
2. Tilt sensor / inclinometer

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the flex joint assembly for wear, tears, or other damage and for any debonding between the material and metal plates.

2. Soak the assembly in a controlled environment at a temperature between 69° and 72°F for at least one hour prior to testing. The test environment should have the same temperature as the soak environment.
3. Mount the assembly rigidly to the base plate of the test fixture and then mount the deflection rod to the top plate of the flex joint assembly. The assembly is aligned so that the anterior-posterior direction is aligned with the long axis of the fixture. Ensure that the initial starting position is 0° ± 1° .
4. Slowly rotate the top rod from the initial starting position to somewhat greater than 15° at a rate of 1 - 2°/second.
5. Calculate the torque at the center of the flex joint. Calculation procedure is described in the section titled **Neck Quasi-static Flexion Test**.

Performance Specifications

Determine the torque for frontal flexion at 15°. The torque certification requirements are as follows:

Frontal Flexion at 15°: 135 - 149 N-m

Typical moment-angle response from the thoracic flex joint under frontal flexion is shown in the graph below.

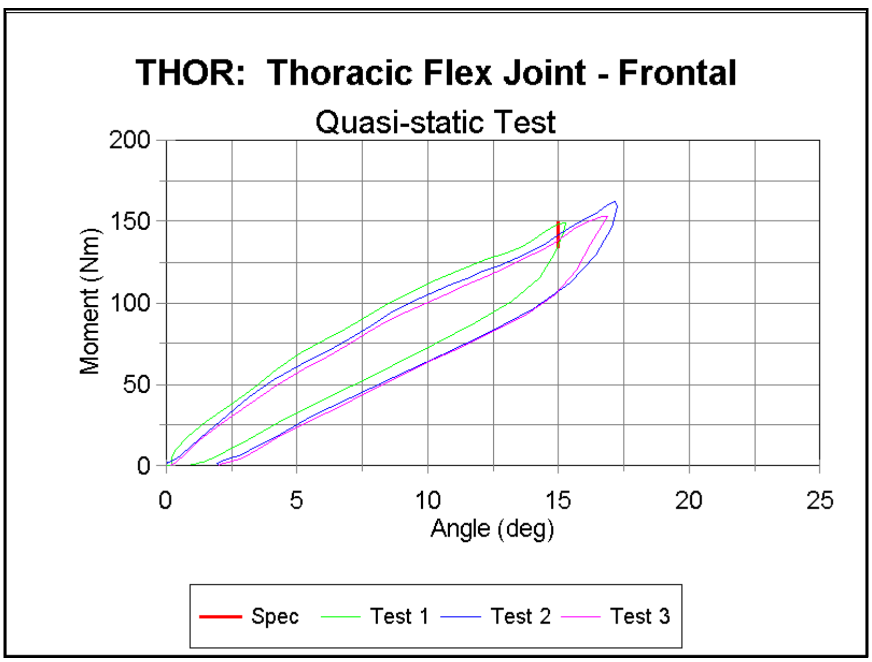


Figure 48. Moment-angle response of thoracic flex joint in quasi-static frontal flexion.

10.3 Lumbar Flex Joint Quasi-static Frontal Flexion Test

Description

The static frontal flexion test of the lumbar flex joint is used to measure its quasi-static moment-angle response when bent in the frontal direction.

Materials

The parts required for the frontal flexion test are:

1. Complete lumbar flex assembly
2. Quasi-static bending fixture (see **Thoracic Flex Joint Quasi-static Frontal Flexion Test**)

Instrumentation

The instrumentation required for the test is:

1. Tension/compression load cell
2. Tilt sensor / inclinometer

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the flex joint assembly for wear, tears, or other damage and for any debonding between the material and metal plates.
2. Soak the assembly in a controlled environment at a temperature between 69° and 72°F for at least one hour prior to testing. The test environment should have the same temperature as the soak environment.
3. Mount the assembly rigidly to the base plate of the test fixture and then mount the deflection rod to the top plate of the flex joint assembly. The assembly is aligned so that the anterior-posterior direction is aligned with the long axis of the fixture. Ensure that the initial starting position is 0° ± 1° .
4. Slowly rotate the top rod from the initial starting position to somewhat greater than 25° at a rate of 1 - 2°/second.
5. Calculate the torque at the center of the flex joint. Calculation procedure is described in the section titled **Neck Quasi-static Flexion Test**.

Performance Specifications

Determine the torque for frontal flexion at 25°. The torque certification requirements are as follows:

Frontal Flexion at 25°: 114 - 126 N-m

Typical moment-angle response from the lumbar flex joint under frontal flexion is shown in the graph below.

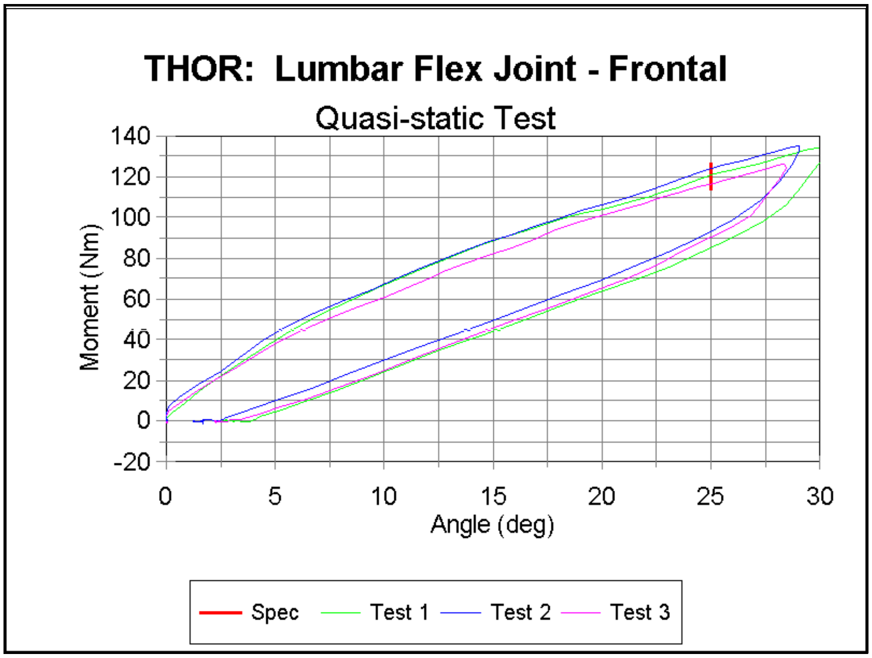


Figure 49. Moment-angle response of lumbar flex joint in quasi-static frontal flexion.

11. THORAX

11.1 Rib Damping Material Quasi-static Compression Test

Description

The rib damping material (EAR Isodamp CN) compression test is a quasi-static test designed to check the force-deflection characteristics of the material for a standard geometry using the material. The results from the test are used to compare with the design reference as given in the Thor-Alpha Drawing Package (Version 1.0). The manufacturer can use the information to aid in the final rib assembly.

Materials

The parts required for the material compression test are:

1. Specimen of the rib damping material (2" x 2" x .575"). Because the height of the specimen is small, 3 layers of the material are used.
2. Any test equipment capable of applying compressive load quasi-statically (e.g. Universal Test Machine).

Instrumentation

The required instrumentation for this test is:

1. Compression Load Cell (minimum capacity 20000 N)
2. Displacement transducer (e.g. LVDT)

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the rib damping material for wear, tears, or other damage.
2. Soak the material in a controlled environment at a temperature between 69° and 72°F for at least 30 minutes prior to testing. The test environment should have the same temperature as the soak environment.
   NOTE: Care should be taken to ensure the ambient temperature is well controlled within the above limits since the material is very temperature sensitive.
3. Mount the material to the base plate of the test fixture. The specimen should be free to slip at both the lower and upper surfaces.
4. Rest the samples on a flat base plate rigidly attached to the test fixture. The loading plate should also be flat. Both the base plate and the loading plate should have a larger area than the specimen. The three layers of the material are laid carefully on top each other. The specimen should be free to slip at both the lower and upper surfaces.

5. Slowly compress the specimen at a rate of 1mm /sec, until about 14% compression is achieved.
6. Measure the compression force using the load cell and the displacement with the displacement transducer.

Performance Specifications

Determine the compression force for compression of 15%. The compression corridor is specified as:

Force at 15% compression (6.6 mm): 16360 - 18070 N

Typical force-deflection response from the compression test is shown in the graph below.

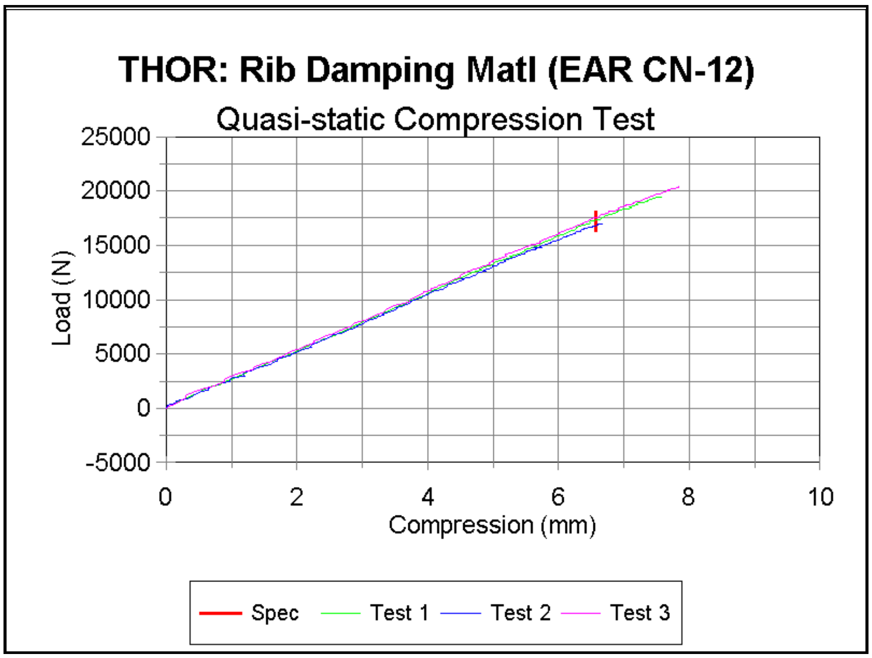


Figure 50. Force-deflection response for rib damping material under quasi-static compression.

11.2 Bib Material Quasi-static Tension Test

Description

The bib material (80A Urethane) tension test is a quasi-static test designed to check the force-elongation characteristics of the material. The results from the test are used to compare with the design reference as given in the Thor-Alpha Drawing Package (Version 1.0). The manufacturer can use the information to aid in the final bib design.

Materials

The parts required for the material tension test are:

1. Specimen of the bib material - 152.4mm x 50.8 mm x 3.2 mm (6" x 2" x 1/8").
2. Any test equipment capable of applying tension load quasi-statically (e.g. Universal Test Machine).

Instrumentation

The required instrumentation for this test is:

1. Tension Load Cell (minimum capacity 1000 N)
2. Displacement transducer (e.g. LVDT)

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the bib material for wear, tears, or other damage.
2. Soak the material in a controlled environment at a temperature between 69° and 72°F for at least 30 minutes prior to testing. The test environment should have the same temperature as the soak environment.
3. Clamp the material between the ends of the test fixture. Approximately, 1" of the material should be clamped at each end. The two ends of specimen should be fixed for the tension test.
4. Slowly pull the specimen at a rate of 1mm /sec.
5. Measure the tension force using the load cell and the displacement with the displacement transducer.

Performance Specifications

The tension corridor is specified as:

Force at 40% elongation (40.6 mm): 560 - 680 N

Typical force-elongation response from the tension test is shown in the graph below.

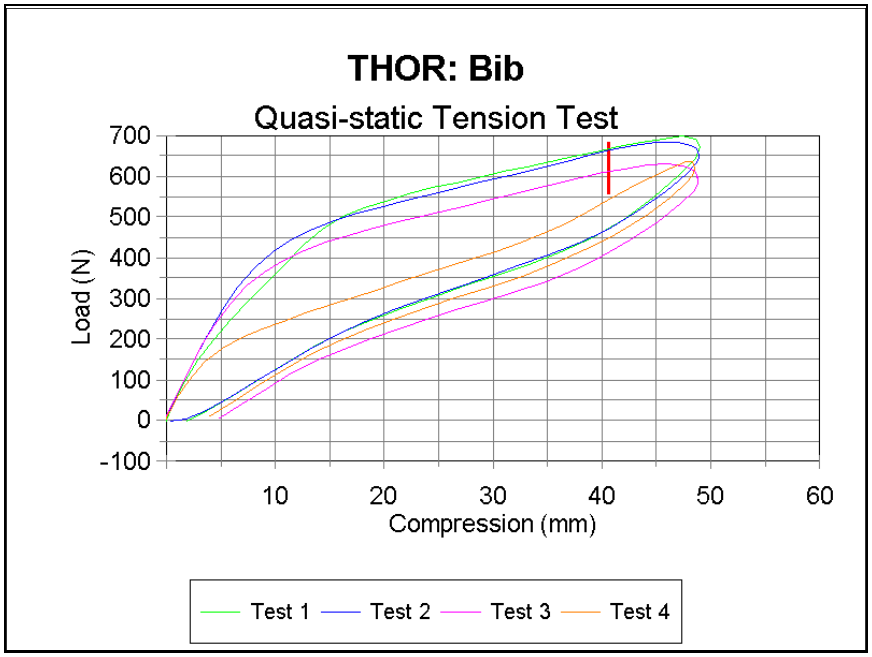


Figure 51. Force-deflection response of jacket material under quasi-static tension.

11.3 Jacket Material Quasi-static Tension Test

Description

The jacket material (Rubatex) tension test is a quasi-static test designed to check the force-elongation characteristics of the material. The results from the test are used to compare with the design reference as given in the Thor-Alpha Drawing Package (Version 1.0). The manufacturer can use the information to aid in the final jacket design.

Materials

The parts required for the material tension test are:

1. Specimen of the jacket material - 152.4mm x 50.8 mm x 3.2 mm (6" x 2" x 1/8").
2. Any test equipment capable of applying tension load quasi-statically (e.g. Universal Test Machine).

Instrumentation

The required instrumentation for this test is:

1. Tension Load Cell (minimum capacity 1000 N)
2. Displacement transducer (e.g. LVDT)

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the jacket material for wear, tears, or other damage.
2. Soak the material in a controlled environment at a temperature between 69° and 72°F for at least 30 minutes prior to testing. The test environment should have the same temperature as the soak environment.
3. The two ends of specimen should Clamp the material between the ends of the test fixture. Approximately, 1" of the material should be clamped at each end. The two ends of specimen should be fixed for the tension test.
4. Slowly pull the specimen at a rate of 1mm /sec.
5. Measure the tension force using the load cell and the displacement with the displacement transducer.

Performance Specifications

The tension corridor is specified as:

Force at 40% elongation (40.6 mm): 16 - 20 N

Typical force-elongation response from the tension test is shown in the graph below.

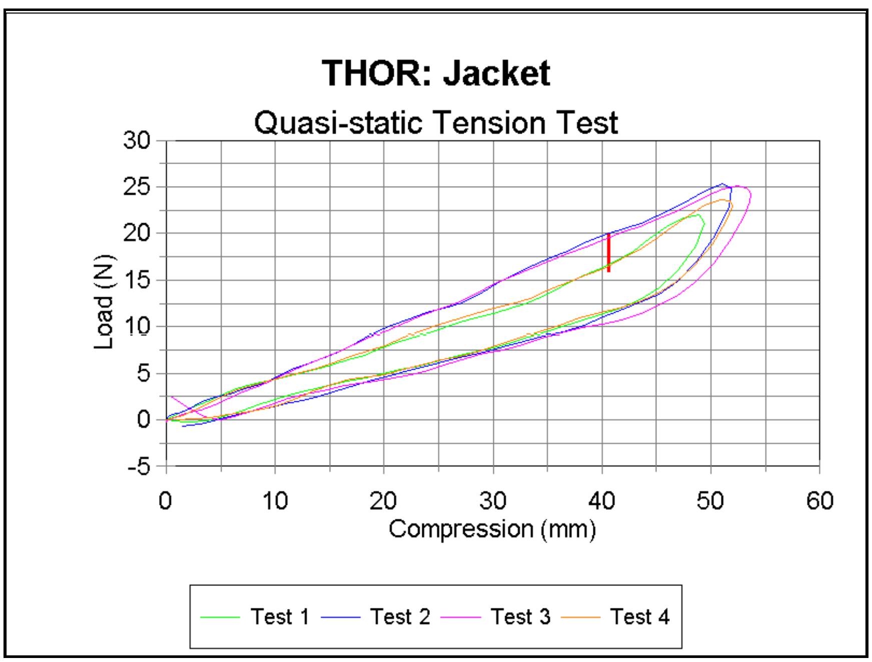


Figure 52. Force-deflection response of bib under quasi-static tension.

12. ABDOMEN

12.1 Abdomen Material Quasi-static Compression Tests

Description

The abdomen material (Charcoal Polyester foam #6 and Sponge Rubber Neoprene/EPDM/SBR) compression tests are quasi-static tests designed to check the force-deflection characteristics of the materials used within the upper and lower abdomen components. The results from the tests are used to compare with the design references as given in the Thor-Alpha Drawing Package (Version 1.0). The manufacturer can use the information to aid in the final abdomen assembly.

Materials

The parts required for the material compression test are:

1. 50.8mm x 50.8mm x 50.8mm (2" x 2" x 2") samples of the two kinds of foam material.
2. Any test equipment capable of applying compressive load quasi-statically (e.g. Universal Test Machine).

Instrumentation

The required instrumentation for this test is:

1. Compression Load Cell (minimum capacity 2000 N)
2. Displacement transducer (e.g. LVDT)

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the specimen for wear, tears, or other damage.
2. Soak the specimen in a controlled environment at a temperature between 69° and 72°F for at least 30 minutes prior to testing. The test environment should have the same temperature as the soak environment.
3. Rest the sample on a flat base plate rigidly attached to the test fixture. The loading plate should also be flat. Both the base plate and the loading plate should have a larger area than the specimen. The specimen should be free to slip at both the lower and upper surfaces.
4. Slowly compress the specimen at a rate of 1 - 5 mm /sec, until about 50% compression is achieved.
5. Measure the compression force using the load cell and the displacement with the displacement transducer.

Performance Specifications

The compression corridors are specified as:

For Charcoal Polyester foam #6:

Load for 50% compression (25.4 mm):	34 - 38 N
Load for 75% compression (38.1 mm):	102 - 118 N

For Sponge Rubber:

Load for 25% compression (12.7 mm):	170 - 190 N
Load for 50% compression (25.4 mm):	440 - 490 N

Typical force-deflection response from the compression tests on the two materials is shown in the graphs below.

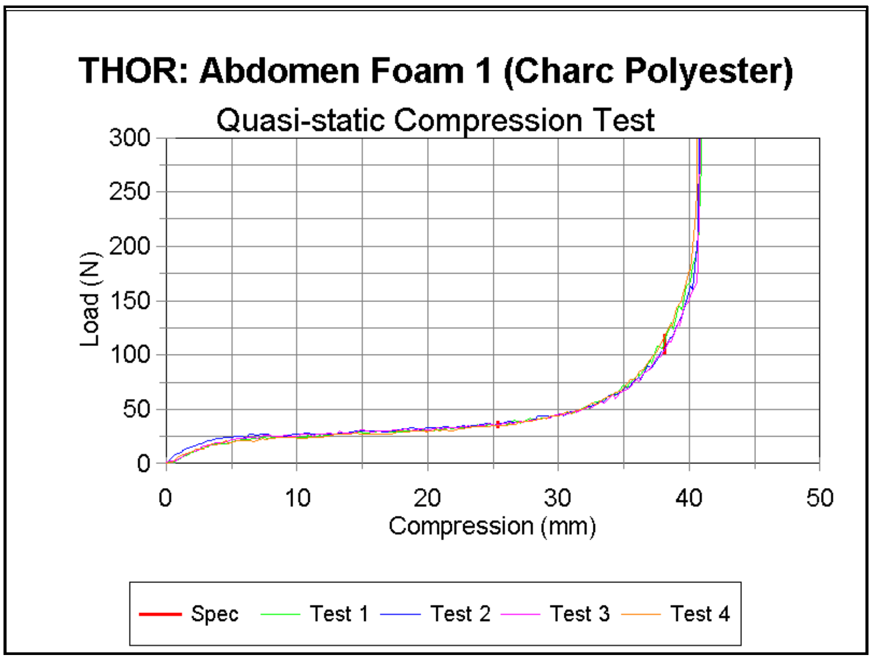


Figure 53. Force-deflection response of charcoal polyester under quasi-static compression.

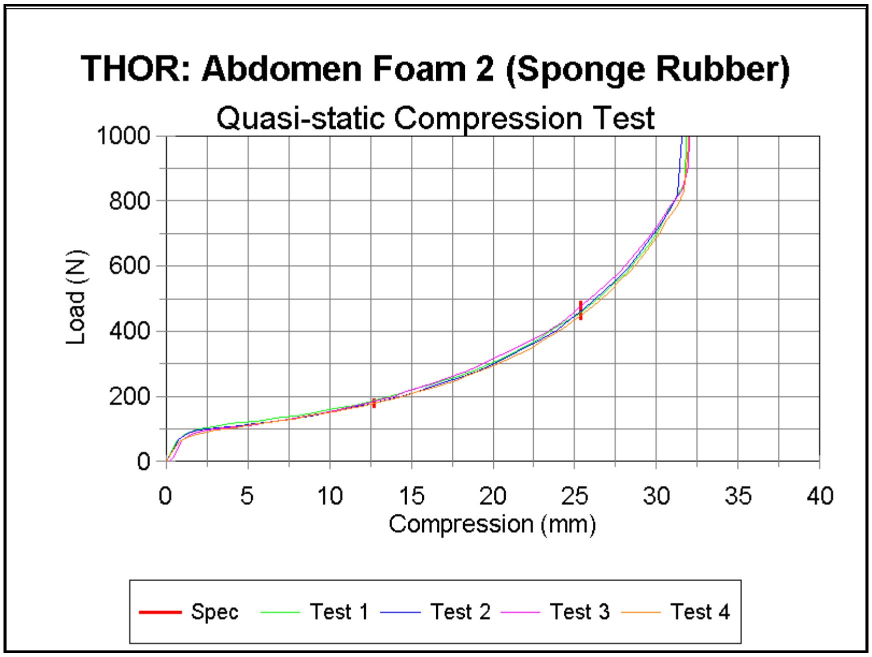


Figure 54. Force-deflection response of Sponge Rubber under quasi-static compression.

13. SHOULDER

13.1 Shoulder Pad and Stop Quasi-static Compression Tests

Description

There are currently no biomechanical targets that have been defined, which the Thor shoulder has to meet. Instead there are quasi-static compression tests for the materials used in the shoulder pad (Ciba-Geigy Urethane RP6410-1) and shoulder stop (Buna-N 50A). The results from the tests are used to compare with the design references as given in the Thor-Alpha Drawing Package (Version 1.0; Drawing T1xxxxxx). The manufacturer can use the information to aid in the final shoulder assembly.

Materials

The parts required for the material compression test are:

1. Sample of size 50.8mm x 50.8 mm x 50.8 mm (2" x 2" x 2") molded from the Urethane material and cut from a sheet of Buna-N
2. Any test equipment capable of applying compressive load quasi-statically (e.g. Universal Test Machine).

Instrumentation

The required instrumentation for this test is:

1. Compression Load Cell (minimum capacity 10000 N)
2. Displacement transducer (e.g. LVDT)

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the specimen for wear, tears, or other damage.
2. Soak the specimen in a controlled environment at a temperature between 69° and 72°F for at least 30 minutes prior to testing. The test environment should have the same temperature as the soak environment.
3. Rest the sample on a flat base plate rigidly attached to the test fixture. The loading plate should also be flat. Both the base plate and the loading plate should have a larger area than the specimen. The specimen should be free to slip at both the lower and upper surfaces.
4. Slowly compress the specimen at a rate of 1 - 5 mm /sec.
5. Measure the compression force using the load cell and the displacement with the displacement transducer.

Performance Specifications

The compression corridors are specified as:

For Ciba-Geigy Urethane RP6410-1:
Load at 40% compression (20.3mm): 3820 - 4420 N

For Buna-N Rubber:
Force at 50% compression (19.1mm): 6920 - 7630 N

Typical force-deflection response from the compression test is shown in the graph below.

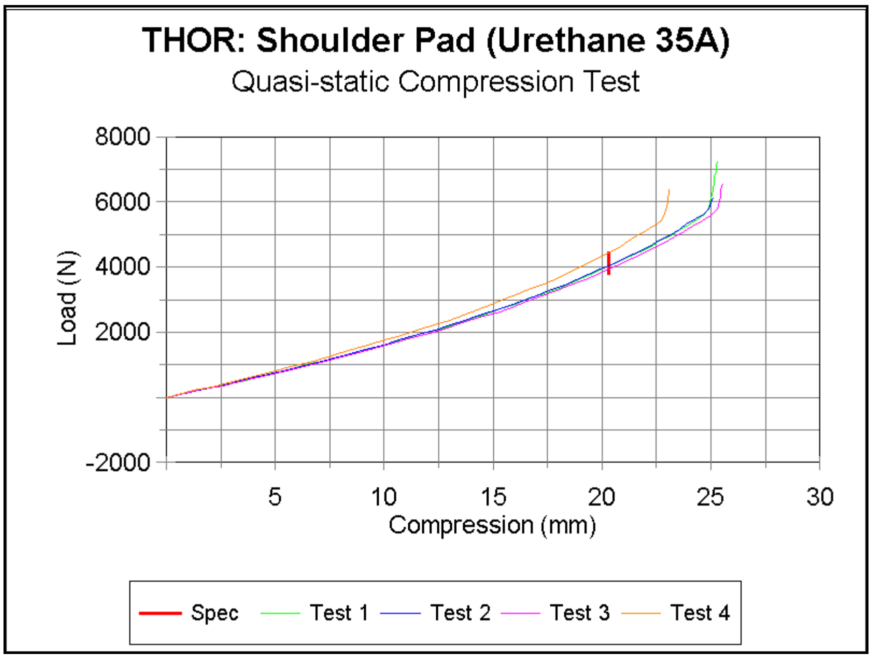


Figure 55. Force-deflection response of shoulder pad under quasi-static compression.

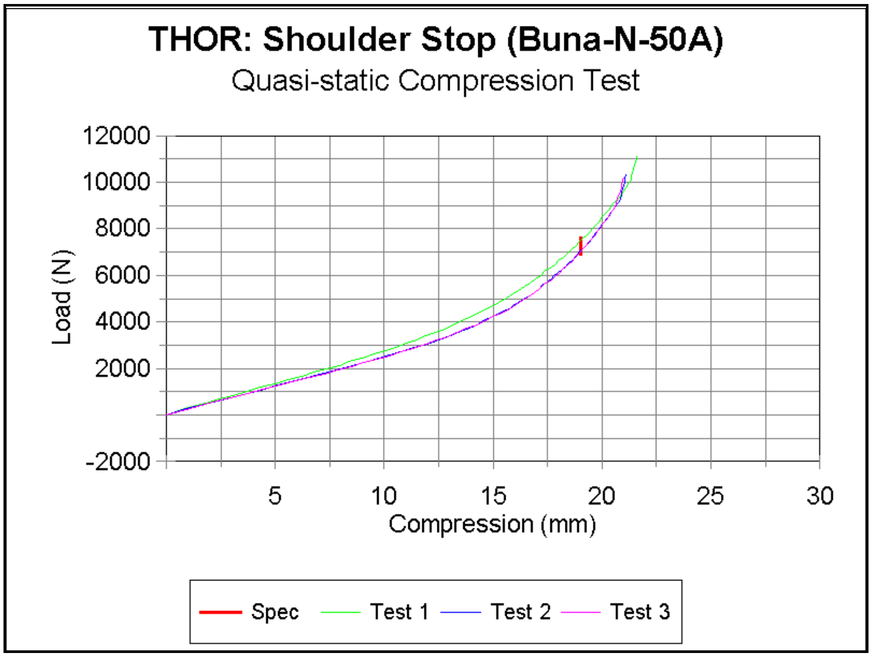


Figure 56. Force-deflection response of Buna-N (shoulder stop) under quasi-static compression.

14. FEMUR

14.1 Femur Puck Quasi-static Compression Tests

Description

The femur material (Neoprene 75A) compression tests are quasi-static tests designed to check the force-deflection characteristics of the materials used as the femur puck. The results from the tests are used to compare with the design references as given in the Thor-Alpha Drawing Package (Version 1.0). The manufacturer can use the information to aid in the final femur assembly.

Materials

The parts required for the material compression test are:

1. A 50.8mm x 50.8mm x 50.8 mm (2" x 2" x 2") sample of the material.
2. Any test equipment capable of applying compressive load quasi-statically (e.g. Universal Test Machine).

Instrumentation

The required instrumentation for this test is:

1. Compression Load Cell (minimum capacity 16 kN)
2. Displacement transducer (e.g. LVDT)

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the specimen for wear, tears, or other damage.
2. Soak the specimen in a controlled environment at a temperature between 69° and 72°F for at least 30 minutes prior to testing. The test environment should have the same temperature as the soak environment.
3. Rest the sample on a flat base plate rigidly attached to the test fixture. The loading plate should also be flat. Both the base plate and the loading plate should have a larger area than the specimen. The specimen should be free to slip at both the lower and upper surfaces.
4. Slowly compress the specimen at a rate of 1 - 5 mm /sec.
5. Measure the compression force using the load cell and the displacement with the displacement transducer.

Performance Specifications

The compression corridor is specified as:

Force at 30% compression (15.2 mm): 14070 - 15120 N

Typical force-deflection response from the compression test is shown in the graph below.

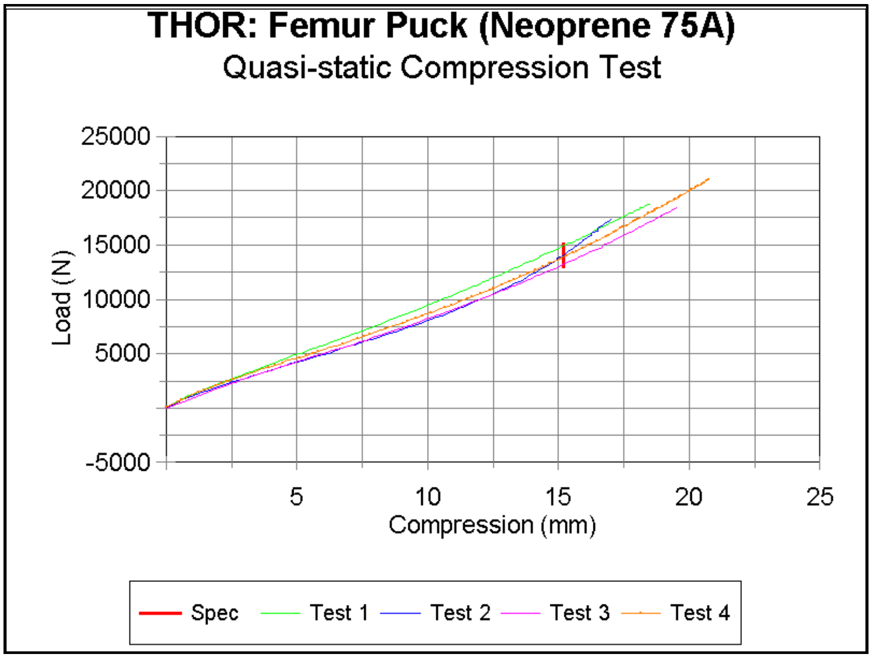


Figure 57. Force-deflection response of femur puck under quasi-static compression.

15. FACE

15.1 Face Foam Material Compression Test

Description

The face foam material (Blue Confor) compression test is a quasi-static test designed to check the force-deflection characteristics of the material used in the face. The results from the tests are used to compare with the design references as given in the Thor-Alpha Drawing Package (Version 1.0). The manufacturer can use the information to aid in the final face assembly.

Materials

The parts required for the material compression test are:

1. A 50.8mm x 50.8mm x 50.8mm (2" x 2" x 2") sample of the Blue Confor material.
2. Any test equipment capable of applying compressive load quasi-statically (e.g. Universal Test Machine).

Instrumentation

The required instrumentation for this test is:

1. Compression Load Cell (minimum capacity 500 N)
2. Displacement transducer (e.g. LVDT)

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the specimen for wear, tears, or other damage.
2. Soak the specimen in a controlled environment at a temperature between 69° and 72°F for at least 30 minutes prior to testing. The test environment should have the same temperature as the soak environment.
3. Mount the specimen to the base plate of the test fixture. The specimen should be free to slip at both the lower and upper surfaces.
4. Slowly compress the specimen at a rate of 1 - 5 mm /sec, until the compression exceeds 80%.
5. Measure the compression force using the load cell and the displacement with the displacement transducer.

Performance Specifications

The compression corridor is specified as:

Load at 50% compression (25.4 mm):	54 - 64 N
Load at 75% compression (38.1 mm):	145 - 170 N

Typical force-deflection response from the compression test is shown in the graph below.

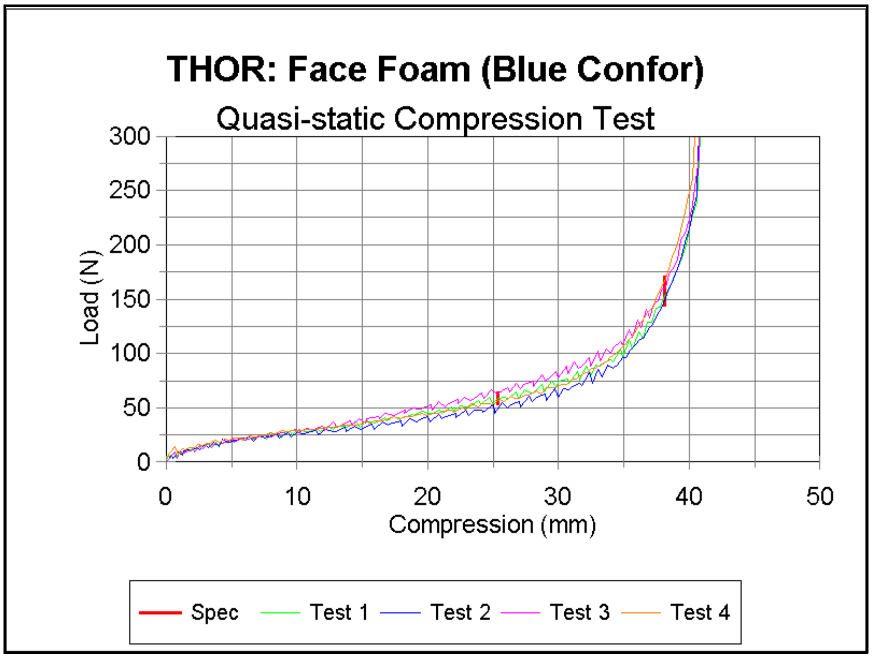


Figure 58. Force-deflection response of face foam under quasi-static compression.

16. LOWER LEG/ANKLE/FOOT

A number of tests are performed on selected components of the leg, ankle, and foot which provide a comparison to design reference values. Some of the tests are quasi-static compression tests which are performed on the deformable materials used in these components. In addition to compression tests, there are number of additional tests that are used to evaluate the performance of the ankle under different rotation motions.

16.1 Quasi-static Heel Pad Material Compression Test

Description

The heel pad material (Neoprene 50A) compression test is a quasi-static test designed to check the force-deflection characteristics of the material. The results from the test are used to compare with the design reference as given in the Thor-Alpha Drawing Package (Version 1.0). The manufacturer can use the information to aid in the final foot assembly.

Materials

The parts required for the material compression test are:

1. Heel pad (nominal size - 63.5 mm x 44.5 mm x 12.7 mm)
2. Any test equipment capable of applying compressive load quasi-statically (e.g. Universal Test Machine).

Instrumentation

The required instrumentation for this test is:

1. Compression Load Cell (minimum capacity 10000 N)
2. Displacement transducer (e.g. LVDT)

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the pad material for wear, tears, or other damage.
2. Soak the pad in a controlled environment at a temperature between 69° and 72°F for at least 30 minutes prior to testing. The test environment should have the same temperature as the soak environment.
3. Rest the heel pad on a flat base plate rigidly attached to the test fixture. The loading plate should also be flat. Both the base plate and the loading plate should have a larger area than the specimen. The specimen should be free to slip at both the lower and upper surfaces.

4. Slowly compress the specimen at a rate of 1 - 5 mm /sec, until about 30% compression is achieved.
5. Measure the compression force using the load cell and the displacement with the displacement transducer.

Performance Specifications

Determine the compression force for compressions of 28%. The compression corridor is specified as:

Load for 28% compression (at 3.5 mm): 4770 - 5830 N

16.2 Quasi-static Tibia Puck Compression Test

Description

The tibia puck material (Neoprene 65A) compression test is a quasi-static test designed to check the force-deflection characteristics of the material. The results from the test are used to compare with the design reference as given in the Thor-Alpha Drawing Package (Version 1.0). The manufacturer can use the information to aid in the final leg assembly.

Materials

The parts required for the material compression test are:

1. Tibia puck (length 31.8 mm; outer diameter 38.1 mm; inner diameter 19.1 mm)
2. Any test equipment capable of applying compressive load quasi-statically (e.g. Universal Test Machine).

Instrumentation

The required instrumentation for this test is:

1. Compression Load Cell (minimum capacity 10000 N)
2. Displacement transducer (e.g. LVDT)

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the puck for wear, tears, or other damage.
2. Soak the puck in a controlled environment at a temperature between 69° and 72°F for at least 30 minutes prior to testing. The test environment should have the same temperature as the soak environment.

3. Rest the tibia puck on a flat base plate rigidly attached to the test fixture. The loading plate should also be flat. Both the base plate and the loading plate should have a larger area than the specimen. The specimen should be free to slip at both the lower and upper surfaces.
4. Slowly compress the specimen at a rate of 1 - 5 mm /sec, until about 50% compression is achieved.
5. Measure the compression force using the load cell and the displacement with the displacement transducer.

Performance Specifications

Determine the compression force for compressions of 28%. The compression corridor is specified as:

Load for 25% compression (7.9 mm):	1270 - 1550 N
Load for 50% compression (15.9 mm):	2750 - 3370 N

16.3 Achilles Spring and Tube Quasi-static Compression Test

Description

This test is a quasi-static test designed to check the force-deflection characteristic of the Achilles spring and the spring and tube combination The result from the test is used to compare with the design reference as given in the Thor-Alpha Drawing Package (Version 1.0). The manufacturer can use the information to aid in the final neck assembly.

Materials

The parts required for the material compression test are:

1. Achilles spring and tube (Buna-N/SBR hose).
2. Any test equipment capable of applying compressive load quasi-statically (e.g. Universal Test Machine).

Instrumentation

The required instrumentation for this test is:

1. Compression Load Cell (minimum capacity 2000 N)
2. Displacement transducer (e.g. LVDT)

The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Test Procedure

1. Inspect the spring and tube for any damage or for permanent set.
2. Mount the spring or the spring and tube combination to a flat, base plate attached to the test fixture. The spring can be retained in a holder, such that sufficient length is exposed for compression. The loading plate should be flat and its area should be larger than that of the spring. The specimen should be free to slip at both the lower and upper surfaces.
3. Slowly compress the spring or the spring and tube at a rate of 1 - 5 mm /sec.
4. Measure the compression force using the load cell and the displacement with the displacement transducer.

Performance Specifications

The force-deflection corridors for the spring and the spring and tube combination are:

Achilles Spring:

Force at 30 mm compression:	715 - 785 N (spring rate of 25 ± 1.3 N/mm)
Maximum compressible length:	> 40.0 mm

Achilles Spring + Tube:

Force at 30 mm compression:	945 - 1155 N

16.4 Quasi-static Ankle Tests

The test procedures for the various quasi-static tests used for evaluating ankle stiffness in the various directions, except for the internal/external rotation are essentially similar. The procedures for these tests are provided in greater detail in the document *Certification Procedures for the Thor-LX/Hybrid III Retrofit Version 3.0-December, 2000*. The general procedure is described in below for the sake of completeness of this document.

Description

The quasi-static tests used as design reference for ankle response are:

1. Dorsiflexion with Achilles
2. Dorsiflexion without Achilles
3. Plantarflexion

Materials

The equipment and fixtures utilized in this test are:

1. Thor-Lx assembly, including tibia (below compressible element), ankle assembly, and foot.

2. Machine capable of vertical travel with application of load (e.g. Universal Testing Machine)
3. Steel cable
4. Rigid fixture to horizontally mount lower leg to universal testing machine
5. Ankle Moment Arm
6. Cable Attachment Bracket

Instrumentation

The instrumentation required for the quasi-static tests is:
1. Lower leg assembly including the following parts, ankle assembly, achilles assembly, tibia assembly, and X, Y, and Z-axis rotary potentiometers.
2. Instrument to measure moment and force.

Test Procedure

1. Inspect the ankle soft stop assemblies for uneven wear, tears, or other damage. Check for smooth rotation of the ankle about all three axes.
2. Soak the ankle, foot, and tibia assemblies in a controlled environment at a temperature between 69 °F and 72 °F for at least four hours prior to testing. The test environment should have the same temperature as the soak environment.
3. Rigidly mount the tibia and align the foot at zero position (0° dorsiflexion, plantarflexion, inversion, and eversion, 0° rotation about Z-axis).
   (Note: For dorsiflexion and plantarflexion, rotation about the Z-axis is undesirable during the quasi-static tests and should be prevented.)
4. Attach the Achilles tendon only for the dorsiflexion with Achilles test. Also, the potentiometer channels should be set according to calibration values provided by the manufacturer and verified for accuracy.
5. Rotate the ankle from the initial starting position to 37-38° inversion or eversion at a rate of 1-2°/second. (Note: Do not rotate beyond 38° to avoid damage as this angle is near the joint mechanical limit.)
6. Calculate the torque at the ankle joint.

Data Processing

The polarity conventions must conform to requirements of the 1996 revision of SAE Recommended Practice J211. The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

The calculation of the moments acting about the ankle are made according to the procedure described in Section 8.1.

Performance Specifications

The angles at which the following torque values are measured should be within the corresponding ranges:

Dorsiflexion with Achilles

Moment Level (Nm)	Angle Range (deg)
40	16.3 - 19.9
92	33.4 - 40.8

Dorsiflexion without Achilles

Moment Level (Nm)	Angle Range (deg)
10	16.6 - 20.2
36	33.5 - 40.9

Plantarflexion

Moment Level (Nm)	Angle Range (deg)
3	28.2 - 34.4
17	44.0 - 53.8

The design references are shown graphically, along with the original biomechanical specifications.

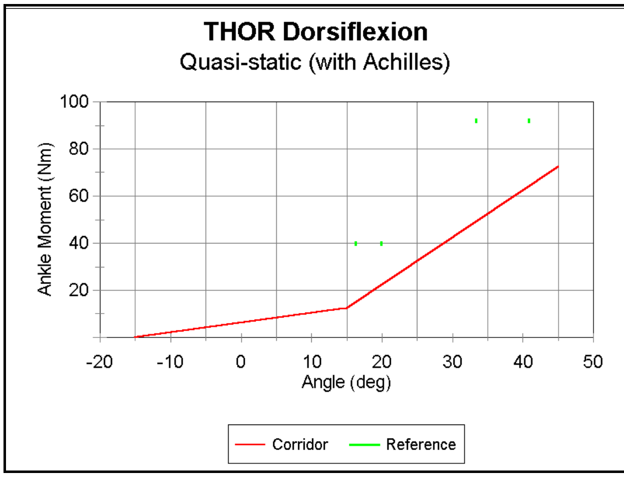


Figure 59. Design reference for quasi-static dorsiflexion with Achilles.

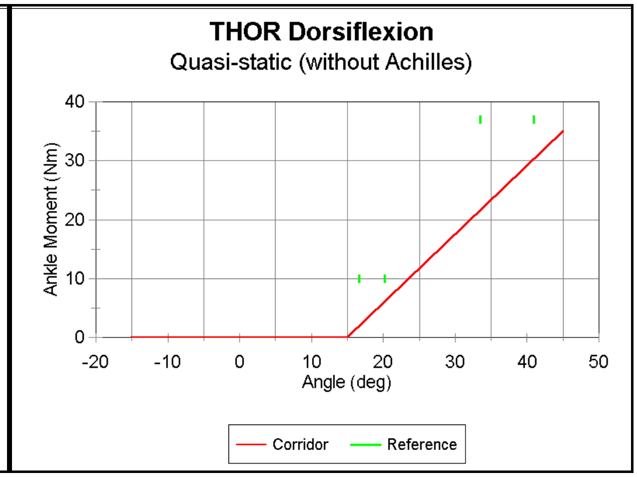


Figure 60. Design reference for quasi-static dorsiflexion without Achilles.

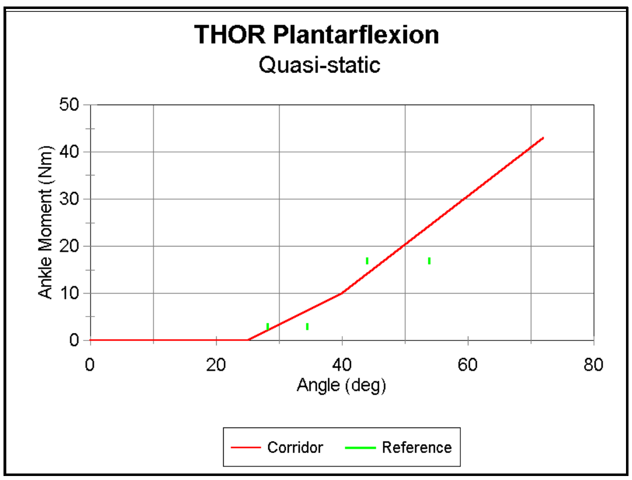


Figure 61. Design reference for quasi-static plantarflexion.

16.5 Quasi-static Z-Rotation Test

Description

The test procedure for evaluating the response of the internal/external rotation block is carried out with a test fixture that allows the unit to be held in place and the outer shell to be rotated.

Materials

The equipment and fixtures utilized in this test are:

1. Top Torque Base from the Thor-Lx assembly (T1AKM011)

2. Machine capable of applying torque about central axis (see accompanying figure for sample fixture).
3. Adapter to mount Top Torque Base to torque machine.

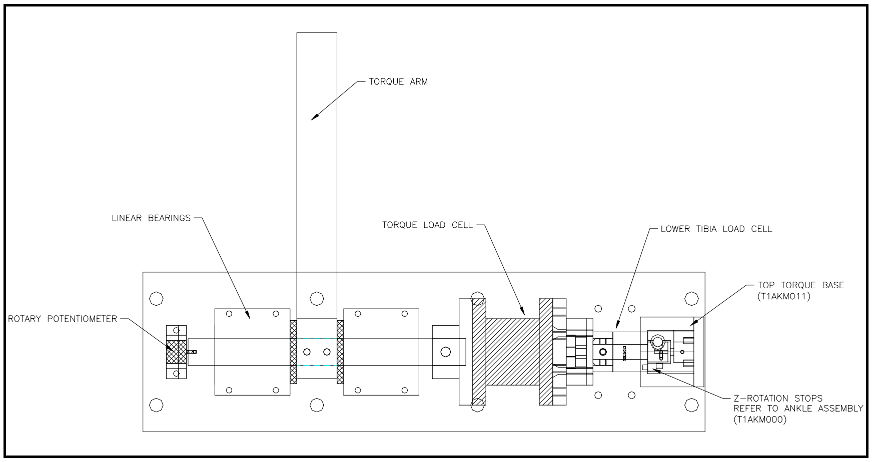


Figure 62. Sample test fixture for determining quasi-static Z-rotation response.

Instrumentation

The instrumentation required for the quasi-static tests is:
1. Rotary potentiometer for measuring Z-rotation.
2. Torque load cell (full scale > 50 Nm)
3. Lower tibia load cell (optional).

Test Procedure

1. Inspect the Z-rotation soft stop assemblies for uneven wear, tears, or other damage. Check for smooth rotation of the ankle subassembly.
2. Soak the ankle assembly in a controlled environment at a temperature between 69 °F and 72 °F for at least one hour prior to testing. The test environment should have the same temperature as the soak environment.
3. Rigidly mount the Top Torque Base to the torque machine. Setup the base at its neutral position (0° internal rotation).
4. Rotate the ankle from the initial starting position to approximately 15° of internal rotation at a rate of 1-2°/second. Rotate the ankle from this position to 15° of external rotation (-15° relative to tibia) in one steady motion, through 0°. Return the ankle to 0° internal rotation.
5. Calculate the torque at the ankle joint.

Data Processing

The polarity conventions must conform to requirements of the 1996 revision of SAE Recommended Practice J211. The laboratory can follow any standard procedure for reducing the data collected from the above sensors, including any low-pass filtering that is generally used by the lab.

Performance Specifications

The angles at which the following torque values are measured should be within the corresponding ranges:

Internal/External Rotation

Angle (deg)	Moment Range (Nm)
15	3.5 - 5.0
-15	-3.5 - -5.0

The design references are shown graphically, along with the original biomechanical specification

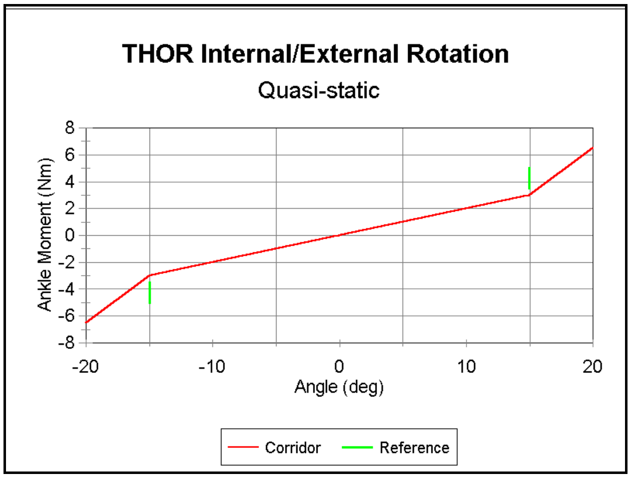


Figure 63. Design reference for quasi-static internal/external rotation.

16.6 Dynamic Inversion/Eversion Tests

The test procedure is available for evaluating the response of the Thor-Lx ankle in dynamic inversion and eversion. Procedure for this tests is provided in greater detail in the document *Dynamic Inversion/Eversion Test for 50th% Thor-Lx/HIIIr (April 16, 2001)*

The general procedure is described in below for the sake of completeness of this document.

Description

The dynamic inversion/eversion test is conducted in a manner similar to the dynamic dorsiflexion test (Section 8.2), using the same pendulum equipment. The test is conducted at 2.0

m/s. A special fixture is attached rigidly to the foot to allow the face of the pendulum to generate the inversion/eversion motion.

Materials

The equipment and fixtures utilized in this test are:

1. NHTSA Dynamic Impactor (described in VRTC document: Certification Procedures for the Thor-LX/Hybrid III Retrofit Version 3.0). The combined mass of the impactor face, ballast, and 1/3 of the supporting tube is 5kg. Because the densities and weights of some materials may vary, slight adjustment of the dimensions may be needed to achieve the same 5kg mass. The supporting structure for the NHTSA Dynamic Impactor is determined by the test facility.
2. Tibia Mounting Fixture
3. Lower leg/ankle/foot assembly below compressible tibia element.
4. Inversion/eversion bracket rigidly attached to foot, to allow impactor to generate the inversion/eversion motion.

The setup for the test is shown in the following figure.

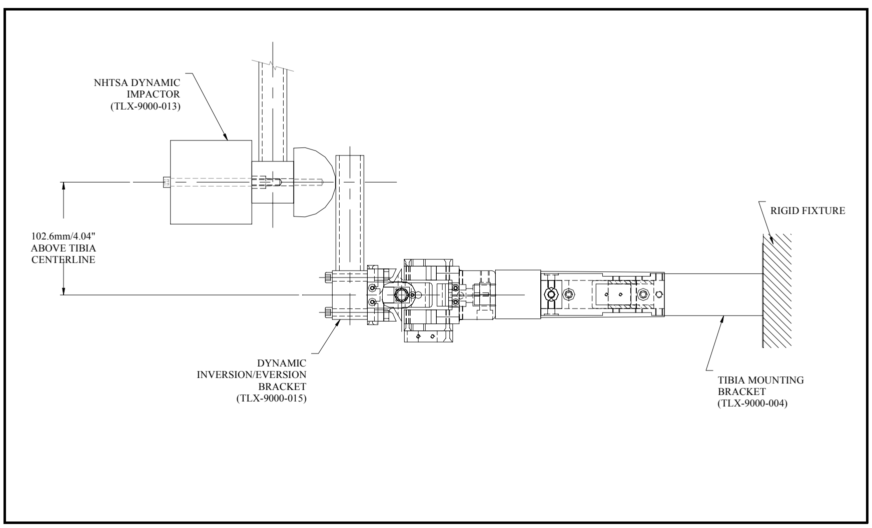


Figure 64. Setup of pendulum fixture for dynamic inversion/ eversion test.

Instrumentation

The instrumentation used for this test is:

1. Five channel lower tibia load cell and X, Y, and Z- axis ankle rotary potentiometers.
2. Instrumentation to measure impactor velocity.

Test Procedure

1. Inspect the ankle soft stops for tears, permanent deformations, or separation from the soft stop brackets. Inspect the foot skin for wear and tears.
2. Soak the ankle, foot, and tibia assemblies in a controlled environment at a temperature between 69°F and 72°F for at least four hours prior to a test. The test environment should have the same temperature as the soak environment.
3. Remove the Tibia Compliant Bushing Assembly and mount the leg to the Tibia Mounting Fixture at the lower flange, with the toe pointing upward. The test fixture must be rigidly secured so that it does not move during impact.
4. Remove the foot skin, and attach the Dynamic Inversion/Eversion Bracket to the foot.
5. Verify that the Achilles spring cable tension is correctly adjusted. (See Thor-Lx/HIIIr User's Manual).
6. Allow the foot to rest in neutral position (15° plantarflexion, 0° inversion and eversion, 0° rotation about the Z-axis) and zero all instrumentation channels except the rotary potentiometers. Potentiometer channels should be set according to calibration values provided by the manufacturer and verified for accuracy (See Thor-Lx/HIIIr User's Manual). Leave the foot in neutral position for impact.
7. Adjust the fixture so that the longitudinal centerline of the pendulum arm is vertical at impact, and the point of impact is 102.6 mm (4.04 in) above the ankle Y-axis pivot point. This is the same distance as in the dynamic dorsiflexion test.
8. Release the pendulum and allow it to fall freely from a height to achieve an impact velocity of 2 ± 0.1 m/s (6.6± 0.3 ft/s). Time-zero is defined as the time of initial contact between the pendulum impactor and the ball of the foot.
9. Record data from the following channels:
   Lower Tibia Load Cell - Fx, Fy, Fz, Mx, My
   X, Y, Z-axis Rotary Potentiometers
   Pendulum acceleration
10. Wait at least 30 minutes between successive impacts to the same foot.

Data Processing

The polarity conventions and data acquisition system must conform to requirements of the 1996 revision of SAE Recommended Practice J211. The lower tibia load cell and accelerometer should be filtered with CFC 600. The rotary potentiometers should be filtered at CFC 180. Suggested sampling rates for the A/D conversion is 10 ksamples/sec

The ankle moment is computed using the formula:

$$M_{ankle} = M_x + aF_y$$

where:
- M_x = moment about X-axis measured by lower tibia load cell
- F_y = force along Y-axis measured by lower tibia load cell
- a = distance between center of lower tibia load cell and subtalar joint (.1054m)

The angle is measured with the X rotary potentiometer. The appropriate offset should be subtracted so that when the foot is perpendicular to the tibia, the angle is computed as zero.

Performance Specifications

The angles at which the following torque values are measured should be within the corresponding ranges:

Peak Lower Tibia Compressive Force	645 - 790 N	(provisional)
Peak Subtalar Resistive Moment	41.5 - 51.0 Nm	(provisional)

The corridors are shown in the following graphs. For the subtalar moment, the corridor is compared with the biomechanical response requirements for inversion and eversion.

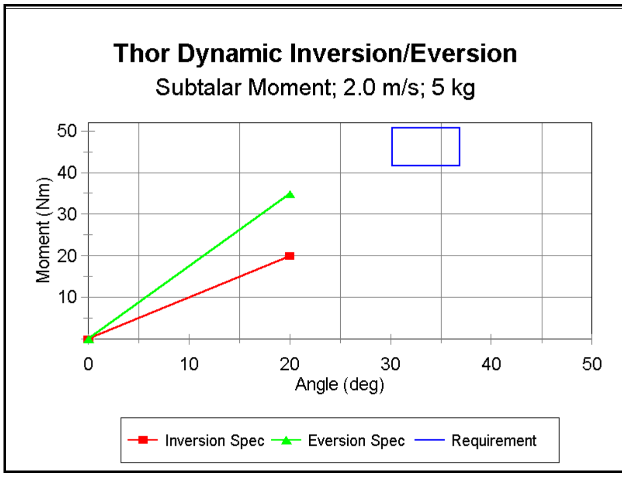


Figure 65. Peak subtalar moment response for dynamic inversion/eversion.

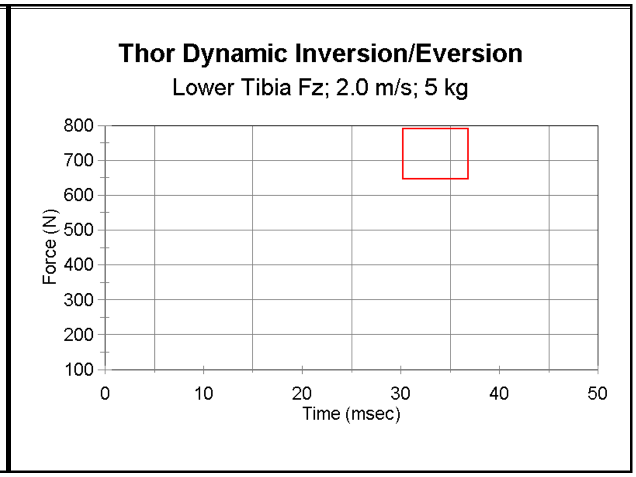


Figure 66. Peak lower tibia Fz response for dynamic inversion/eversion.